

**“TIQXMMI” MILLIY TADQIQOT UNIVERSITETI HUZURIDAGI ILMIY
DARAJALAR BERUVCHI DSc.03/31.03.2022.T/FM.10.04 RAQAMLI
ILMIY KENGASH**

FUNDAMENTAL VA AMALIY TADQIQOTLAR INSTITUTI

SHAYMATOV SANJAR RUZIMUROTOVICH

**GRAVITACION RELYATIVISTIK NAZARIYALARIDA KOMPAKT
ASTROFIZIK OB'EKTLARNING EVOLYUTSIYASI VA DINAMIKASI**

01.04.02-Nazariy fizika

**FIZIKA-MATEMATIKA FANLARI DOKTORI (DSc)
DISSERTATSIYASI AVTOREFERATI**

Toshkent – 2022

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**Оглавление автореферата диссертации
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Fizika-matematika fanlari doktori (DSc) dissertatsiyasi mavzusi O‘zbekiston Respublikasi Vazirlar Mahkamasi huzuridagi Oliy attestatsiya komissiyasida № B2022.3.DSc/FM196 raqami bilan ro‘yxatga olingan.

Dissertatsiya “TIQXMMI” Milliy tadqiqot universiteti huzuridagi fundamental va amaliy tadqiqotlar institutida bajarilgan.

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Ilmiy darajalar beruvchi ilmiy
kengash raisi o‘rinbosari f.-m.f.d.

E.X. Karimbayev

Ilmiy darajalar beruvchi ilmiy
kengash ilmiy kotibi f.-m.f. bo‘yicha PhD

B.M. Narzilloev

Ilmiy darajalar beruvchi ilmiy
kengash huzuridagi
ilmiy seminar raisi f.-m.f.d.

KIRISH (fan doktori (DSc) dissertatsiyasi annotatsiyasi)

Dissertatsiya mavzusining dolzarbligi va zaruriyati.

Zamonaviy astronomik kuzatuvlar yordamida yaqin qo'shaloq sistemalardagi qora o'ralarning birlashishi natijasida gravitatsion to'lqinlarni aniqlash va M87 va Sgr A* galaktikalari markazida joylashgan o'ta massiv qora o'ra soyasining taxlili natijalari fazo-vaqt geometriyasining mohiyatini va kuchli maydon rejimida gravitatsion o'zaro ta'sir hodisasini juda oson tushuntirish imkonini bermoqda. Bu kabi zamonaviy kuzatuvlar tabiatda qora o'ralar mavjudligi bo'yicha nafaqat kuchli dalil sifatida balki qora o'ralar parametrlarini aniq o'lchash bilan bog'liq bo'lgan muamolarni tekshirishda muhim omil sifatida qaralmoqda. Lekin, bu faktga qaramay, hozirgi bevosita va bilvosita astronomik kuzatuvlar yuqori o'lchamdagi ($D > 4$) qora o'ralarning tabiati, shakllanishi va hosil bo'lishi kabi savollarga oydinlik kiritmadi. Shuningdek, Eynshteynning gravitatsiya nazariyasi cheklangan bo'lib, misol uchun qora o'ra markazida hosil bo'ladigan singulyarlikni tushuntirib berolmaydi. Bu esa umumiy nisbiylik nazariyasining kamchiliklaridan biri bo'lib qolmoqda. Umumiy nisbiylik nazariyasida, bu kabi ochiq savollar o'z navbatida yangi modellar va muqobil gravitatsion nazariyalarni talab qilishga olib keladi.

Respublikamizda keyingi yillarda relyativistik astrofizika sohasida eksperimental va fundamental tadqiqotlarni xalqaro darajada rivojlantirishga katta e'tibor qaratilmoqda. Mamlakatimizda ilm-fanni barcha yo'nalishlarini rivojlantirishda kuzatuv va nazariy tadqiqotlarni amalga oshirish qo'llab-quvvatlanmoqda. Ushbu tadqiqotlar relyativistik astrofizika sohasida muhim ahamiyat kasb etadi va 2017-2021 yillarda O'zbekiston Respublikasini yanada rivojlantirish bo'yicha Harakatlar strategiyasida o'z aksini topgan. Natijada Respublikamizda yuqori va xalqaro miqyosda ilmiy tadqiqotlar olib borish orqali gravitatsion kompakt ob'ektlarning nazariy va relyativistik astrofizikasi rivojlanib borayotganligini ta'kidlash mumkin. Ayniqsa umumiy nisbiylik nazariyasining yangi jihatlarini/ta'sirlarini o'rganishda astrofizik qora o'ralarning optik va energetik xossalarini, ochiq singulyarlik va qora o'ra yechimlarini zarralarning dinamikasi orqali tekshirish yo'li bilan amalga oshirilayotgan tadqiqotlar muhim ahamiyat kasb etmoqda. Shuni ham ta'kidlash joizki, Respublikada relyativistik astrofizikaning rivojlanishi natijasida kompakt gravitatsion ob'ektlar tabiatining muhim jihatlarini o'rganish uchun olimlar tomonidan jiddiy vazifalar qo'yilganligi sababli mamlakatimizda shu soha bo'yicha yangi yo'nalishlar paydo bo'lib bormoqda.

Ushbu dissertatsiya tadqiqoti davlat normativ hujjatlarida va O'zbekiston Respublikasi Prezidentining 2017 yil 7 fevraldagi PQ-4947-sonli "O'zbekiston Respublikasini yanada rivojlantirish bo'yicha Harakatlar strategiyasi", 2017 yil 17 fevraldagi PQ-2789-sonli "Fanlar akademiyasi faoliyatini yanada takomillashtirish, ilmiy ishlarni tashkil etish, boshqarish va moliyalashtirish bo'yicha chora tadbirlar" va 2018 yil 29 noyabrdagi "2019-2021 yillarda O'zbekistonda tarkibiy islohotlarning asosiy yo'nalishlari bo'yicha yo'l-xaritasi to'g'risida"gi Qarorlari,

hamda ushbu sohadagi boshqa me'yoriy-huquqiy hujjatlarda belgilangan vazifalarni amalga oshirishda tasdiqlangan vazifalariga mos keladi.

Tadqiqotning respublika fan va texnologiyalari rivojlanishi-ning ustuvor yo'nalishlariga muvofiqligi. Mazkur dissertatsiya tadqiqot respublikada fan va texnologiyalarni rivojlantirishning II. «Energetika, energiya va resurs tejamkorligi» ustuvor yo'nalishi doirasida bajarilgan.

Dissertatsiya mavzusi bo'yicha xalqaro ilmiy tadqiqotlar sharhi.

Turli xil gravitatsion modellarda qora o'raning shakllanishi va dinamikasini o'rganish va kuchli maydon rejimidagi tashqi maydonlar va zarralarning ta'ziri orqali qora o'ra hodisalar gorizontining barqarorligini tekshirish, qorong'u materiya maydonini qora o'ralarning dinamikasiga ta'sirini modellashtirish bo'yicha tadqiqotlar va qora o'ralarning energetik xosalarini o'rganish bo'yicha etakchi tadqiqot markazlari va muassasalari, ya'ni Maks Plank gravitatsion Fizika instituti (Germaniya), Frankfurt universiteti (Germaniya), Universitetlararo Astronomiya va Astrofizika markazi (Hindiston), Kaliforniya texnologiya instituti (CalTech, AQSh), Chikago universiteti (AQSh), Sharqiy O'rta er dengizi universiteti (Tukiya), Nazariy Fizika instituti (Xitoy), Fizika va yarimo'tkazgich fanlari ilmiy tadqiqot markazi (Koreya Respublikasi), Tata Fundamental tadqiqotlar instituti (Hindiston), Opavadagi Sileziya universiteti (Chexiya Respublikasi), Nazarboyev universiteti (Qozog'iston), Fudan universiteti (Xitoy), Ulug'bek nomidagi Astronomiya instituti (O'zbekiston) va Fundamental va amaliy tadqiqotlar instituti (O'zbekiston) va boshqalar tomonidan ilmiy taqadqiqotlar olib borilmoqda.

Qora o'ra evolyutsiyasida ikkita asosiy jarayon mavjud bo'lib, ya'ni moddalarning o'z tortishish maydoni ta'sirida gravitatsion kollapsi (markazga qulashi) va moddalarning mavjud bo'lgan gravitatsion markazga akkretsiyalanishi (to'planishi) hisoblanadi. Ikkala jarayonning ham ishlashi uchun zaruriy shart sifatida gravitatsion kollapsiga uchraydigan moddalarga yoki markzaga to'planiuvchi zarralarga ta'sir qiluvchi natijaviy kuch har doim tortishuvchi tabiatga ega bo'lish shart. Ma'lum bo'ldiki, bu odatiy to'rt o'lchamli fazoda aylanish momenti noldan farqli bo'lgan kollapsiga uchrovchi va markazga top'lanuvchi moddalar uchun har doim o'rinli bo'ladi. Agar to'rt o'lchamli fazoda natijaviy maydon har doim tortuvchi hususiyatga ega bo'lsa, u holda yuqori o'lchamli fazolarda natijaviy maydon qanday tabiatga ega ekanligini bilish muhim hisoblanadi. Shu nuqtai nazardan, qora o'ralarning yangi jihatlarini o'rganish muhim ahamiyat kesb etadi, ya'ni yuqori o'lchamlarda qora o'ralarning shakllanishi uchun bu ikkita jarayonning bajarilishini tekshirish muhim hisoblanadi. Agar bu ikkala jarayon ham aylanuvchi qora o'raning hosil bo'lishi uchun yuqori o'lchamli fazolarda ishlamasa ($D > 5$), natijada kosmik senzura hodisasi hatto zarralarning birinchi tartibli yaqinlashishi uchun ham o'rinli bo'lishini taxmin qilish mumkin. Bunday vaziyatda sof Lovelok gravitatsiya nazariyasi markaziy o'rinni egallashi va yuqorida aytib o'tilgan ikkala jarayon ham qora o'ralarning shakllanishi uchun ishlay olish yoki olmasligini yuqori o'lchamli fazolarda tekshirish imkoniyatini berishi mumkin.

Muammoning o'rganilganlik darajasi.

Turli tadqiqot markazlari va institutlarining ko'plab olimlari tomonidan o'rganish darajasiga kelsak, Hind olimlari (N. Dadhich, P. Joshi, A. Mishra, S. Sarkar, M. Patil, R. Ghosh va boshqalar.), Yapon olimlari (I. Takahisa, H. Tomohiro, K. Masashi), italiyalik olimlar (K. Bambi, L. Modesto, D. Malafarina, O. Zanotti), Chex olimlari (Z. Stuchlik, M. Kolos, J. Schee, J. Kovar, V. Karas), nemis olimlari (K. Lemmerz, L. Rezzolla, J. Kunz, Ye. Hackmann, D. Kunst, V. Perlik), Xitoy olimlari (B. Chen, J. Jiang, B. Ge), Koreya Respublikasi olimlari (B. Gwak) va boshqalar gravitatsiyaning turli nazariyalarida kosmik senzura hodisasini tekshirib ko'rish orqali qora o'ralarning shakllanishi va qora o'ralar gorizontining barqarorligini o'rganish bo'yicha nazariy va kuzatuv tadqiqotlari o'tkazilgan. Biroq, bu muammolar Eynshteynning gravitasiya nazariyalarida ham, Lovelock nazariyasida ham yuqori o'lchamdagi $D > 4$ qora o'ralar uchun hali to'liq o'rganilmagan.

So'nggi tadqiqotlar va kuzatishlar shuni ko'rsatadiki, zaryadlangan zarrachalarning harakati va AYAG dan chiqadigan zarracha oqimlari o'rtasida bog'liqlik mavjud. Shu munosabat bilan, ko'plab olimlar tomonidan turli vaziyatlarda keng tahlil ishlab chiqilgan, masalan, Hind (M. Wagh, S. Dhurandhar, N. Dadhich), Chex (Z. Stuchlik, M. Kolos va boshqalar), Ukraina (O. Zaslavskii), Italiya (D. Malafarina, Ye. Barausse), O'zbek (B. Ahmedov va boshqalar), Kanada (V. Frolov, va boshqalar.) va boshqa olimlar magnit maydonning qora o'ralar va akkretsiya disklardan energiya olish mexanizmlariga ta'siri o'rganilgan. Biroq, ushbu tadqiqotlarning hech biri magnit maydonning mavjudligi aksial simmetrik fazo vaqtini vujudga kelishiga sababchi bo'ladigan magnetlangan qora o'ra yechimini ko'rib chiqmagan.

Dissertasiya tadqiqotining dissertasiya bajarilgan ilmiy-tadqiqot muassasasi ilmiy-tadqiqot ishlari rejalari bilan bog'liqligi.

Dissertasiya tadqiqoti 2021-2022 yillar davomida Fundamental va amaliy tadqiqotlar instituti va Astronomiya instituti ilmiy-tadqiqotlar rejasining F-FA-2021-432 "Kichik massali rentgen binar sistemalari uchun sun'iy yo'ldoshlardan olingan ma'lumotlarni tahlil qilish va qayta ishlash" (2021–2026) ilmiy loyihalari doirasida bajarilgan.

Tadqiqotning maqsadi qora o'ra shakllanishining batafsil tavsifiga va uning yuqori o'lchamdagi $D > 4$ qora o'ra gorizontining barqarorligiga ta'siriga olib keladigan formalizmni ishlab chiqish, ideal qorong'u moddaning turli vaziyatlarda zarralar va qora o'ralar dinamikasiga ta'siri, ergosferaning kengayishi tufayli katta energiya manbai bo'la oladigan magnitlangan Raysner-Nordstrom qora o'rasining tabiati, shuningdek, olingan natijalarni galaktikalar markazlarida mavjud bo'lgan qorong'u moddaning taqsimotiga, qora o'ralarning muqobil modellarining ishonchlilik chegaralarini aniqlashga va astrofizik kuzatuvlarni tushuntirishda AYAGdan ajraladigan yuqori energiyani tavsiflashga qo'llashdan iborat.

Tadqiqotning vazifalari:

moddaning barqaror aylana orbitalarda gravitatsion ob'ekt atrofidagi harakati natijasida yuzaga keladigan akkretsiya jarayoni orqali yuqori o'lchamdagi aylanadigan qora o'ralarning shakllanishini o'rganish;

Eynshteyn Lovlok gravitasiyasida yuqori o'lchamdagi qora o'ralarning atrofidagi zarralarning barqaror aylana orbitalarini o'rganish; aylanadigan qora o'raning yuqori $D > 4$ va kichik $D < 4$ o'lchamlarda zarralarning chiziqli va nochiziqli ta'sirlari uchun overspin/ovircharj jarayonini o'rganish orqali kosmik senzura hodisasini tekshirishning umumiy formalizmini ishlab chiqish;

turli gravitasiya nazariyalarida qora o'ralar atrofidagi zarralar harakati dinamikasiga qorong'u moddaning ta'sirini o'rganish;

Sgr A* va M87 galaktikalari markazida ideal qorong'u moddaning taqsimlanishi orqali uning qiymatini hisoblash;

magnitlangan qora o'ra atrofidagi aksial-simmetrik fazo-vaqt geometriyasini o'rganish va neytral va zaryadlangan zarralar uchun Penrouz jarayonidan foydalangan holda energiya samaradorligini topish.

Tadqiqotning ob'ekti yuqori o'lchamlarda qora o'ralarning evolyutsiya jarayonlari, gravitatsiyaning turli nazariyalarida astrofizik qora o'ralar atrofidagi elektromagnit, gravittasion va qorong'u modda maydonlari hisoblanadi.

Tadqiqotning predmeti yuqori o'lchamlarda qora o'raning hosil bo'lishi, uning dinamikasi, shuningdek, qora o'ra gorizonti barqarorligini yuqori o'lchamlarda tekshirish, qorong'u moddaning kuzatuv ma'lumotlari bilan bog'liq astrofizik jarayonga ta'siri va aksial simmetrik magnitlangan qora o'raning fazo-vaqtida energiya samaradorligi hisoblanadi.

Tadqiqotning usullari. Dissertatsiyada umumiy nisbiylik nazariyasi va differensial geometriya affin metrikasining matematik apparatlaridan, zarralar dinamikasi va maydonlarining differentsial tenglamalarini echishning analitik va sonli usullaridan foydalanganmiz.

Tadqiqotning ilmiy yangiligi quyidagilardan iborat:

Ilk bor yuqori o'lchamlarda qora o'ra hosil bo'lish jarayonlari o'rganildi; Eynshteynning gravitatsiya nazariyasida akkretsiya diskda barqaror aylana orbitalar mavjud bo'lmasligi va shuning uchun yuqori o'lchamlarda ($D > 4$) aylanuvchi qora o'ra hosil bo'lishi mumkin emasligi ko'rsatilgan;

ilk bor aylanadigan qora o'ralarning yuqori o'lchamlarda ovirspin jarayonini o'rganish orqali, kosmik senzura hodisasini tekshirish uchun umumiy formalizm ishlab chiqildi; kosmik senzura hodisasi $D > 5$ o'lchamlarda har doim mavjud bo'lishi ko'rsatildi;

ilk bor ekstremal va ekstremalga yaqin (2+1) o'lchamli qora o'ralari Eynshteyn va Eynshteyn-Gaus-Bonet gravitasiya nazariyalarida ovircharj jarayoni bajarilishi mumkinligi ko'rsatildi, bu esa kosmik senzura hodisasini (2+1) o'lchamda buzulishiga olib keladi;

ilk bor ideal qorong'u moddaning zarralar harakati dinamikasiga, qora o'ralardan energiya ajralishi samaradorligiga, shuningdek qora o'ralarning dinamikasiga ta'sirini o'rganish orqali formalizm rivojlantirildi; uzoqdagi

kuzatuvchining nuqtai-nazaridan, vakumdagi Kerr qora o'rasini aylanish parametri katt bo'lgan va qorong'u modda hamda tashqi magnit maydonda joylashgan qora o'radan ajratish imkoni yo'qligi ko'rsatildi;

ilk bor ideal qorong'u modda va kosmologik doimiyning birgalikdagi ta'sirini o'rganish orqali formalizm taqdim etildi; RN-dS qora o'rasi uchun kosmologik doimiyning itarishish effekti qorong'u moddaning tortishish ta'siridan ustunlik qilishi mumkin bo'lgan ma'lum bir chegarasidan keyin uning gorizontini buzilishiga olib keladigan ovicharj jarayoni bajarilmasligi ko'rsatildi;

ilk bor aksial simmetrik magnitlangan qora o'rasi fazo-vaqtning geometriyasi va o'ziga xos xususiyatlari o'rganildi va Penrouz jarayoni orqali neytral va zaryadli zarralar uchun aksial simmetrik magnitlangan qora o'rasining magnit maydonini energiya ajralish samaradorligiga ta'siri ko'rsatildi; magnitlangan Raysner-Nordstrom qora o'rasi ham huddi Kerr qora o'rasi kabi katta energiya rezervuari bo'la olishi ko'rsatildi.

Tadqiqotning amaliy natijalari quyidagilardan iborat:

Eynshteynning gravitاسiyasida yuqori o'lchamlarda akkresion diskda barqaror aylana orbitalar hosil bo'lishi mumkin emasligi va shuning uchun $D > 4$ o'lchamlarda aylanadigan qora tuynuk hosil bo'lishi mumkin emasligi isbotlangan;

$D > 5$ bo'lganida barqaror aylana orbitalarning yo'qligi, aylanadigan qora o'ralar uchun overspin jarayoni hatto chizqli akkretsiya jarayoni ta'sirida ham sodir bo'lmasligi ko'rsatilgan;

qorong'u modda va magnit maydonning o'zaro ta'siri qora o'ra aylanish parametrini $a/M \approx 0.8$ qiymatiga qadar taqlid qilishi mumkinligi ko'rsatilgan; ishlab chiqilgan modelga assoslanib ideal qorong'u moddaning yuqori va quyi diapazonlari Sgr A* uchun $\lambda \sim (10^{-21} - 10^{-20})$ va M87 uchun esa $\lambda \sim (10^{-12} - 10^{-11})$ tartibida bo'lishligi topilgan;

ideal qorong'u moddaning tortishish ta'siridan kosmologik doimiyning itarish ta'siri ustunlik qiladigan aniq chegara qiymati uchun analitik ifodasi topilgan; bu qiymatidan katta qiymatlarda RN-dS qora o'rasi uchun ovircharj jarayoni sodir bo'lmasligi ko'rsatilgan va shuning uchun kosmik senzura hodisasiga qat'iy rioya qilinadi;

hatto neytral zarra uchun ham aksial simmetrik ekstremal magnitlangan Reissner-Nordstrom qora o'rasi ($Q = M$) holati uchun Penrouz jarayoni orqali olingan energyaning samarador qiymati ekstremal Kerr ($a = M$) qora o'rasinikidan ($\approx 20\%$) deyarli ikki baravar ($\approx 50\%$) kattaligi topildi.

Tadqiqot natijalarining ishonchliligi. Dissertatsiya ishida zamonaviy raqamli usullar va dasturlar bilan bir qatorda umumiy nisbiylik nazariyasining standart usullari hamda matematik va nazariy fizika metodlaridan foydalanilganligi, olingan nazariy natijalar mavjud nazariy ma'lumotlar va zamonaviy astronomik kuzatuv hamda boshqa olimlarning ilmiy ishlari natijalari bilan ham tekshirilganligi va taqqoslanganligi va olingan natija xulosalari kuchli gravitatsion rejimida kompakt ob'ektlar maydon nazariyasining umumiy tamoyillariga mos kelishi bilan izohlanadi.

Tadqiqot natijalarining ilmiy va amaliy ahamiyati.

Dissertatsiyadagi tadqiqot natijalarining ilmiy ahamiyati yuqori o'lchamdagi $D > 4$ qora o'ralarning yangi va o'ziga xos xususiyatlarini yaxshiroq tushunish maqsadida umumiy ma'lumot va kuchli matematik dalillarni to'plash uchun aylanuvchi qora o'ralarning shakllanish jarayonini tahlil qilish va zarralarning dinamikasi yordamida ularning ovirspin jarayonini o'rganish orqali kosmik senzura hodisasini tekshirish uchun formalizm ishlab chiqishdan iborat. Bundan tashqari, energiyali zarralar akkretsiyon diskidagi o'zaro to'qnashuvlar natijasida hosil bo'ladi va diskning yorqinligi uning atrofidagi fazo vaqtining asosiy geometriyasiga bog'liq bo'ladi. Lekin, haqiqiy vaziyatda ob'ektni vakuumda joylashgan deb hisoblash mumkin emas, chunki qorong'u modda taqsimoti galaktikalar markazida mavjudligi ma'lum. Shuningdek, magnit maydonlar qora o'ralar atrofida, ayniqsa ularning gorizontiga yaqin joylarda zaryadlangan zarralar dinamikasida muhim rol o'ynaydi. Shuning uchun, akkretsiyon disk kuzatuvlaridan olingan xulosalarga ishonch hosil qilish uchun tashqi moddalar va magnit maydonlarining diskdagi zarralarga ta'sirini o'rganish muhim ahamiyat kasb etadi.

Dissertatsiyadagi tadqiqot natijalarining amaliy ahamiyati shundan iboratki, kuzatuv nuqtai nazaridan olingan natijalar akkretsiya diski chiqaradigan elektromagnit nurlanishni kuzatish natijasida ichki turg'un aylana orbitani (ITAO) aniqlash orqali manba aylanish parametrining aniq qiymatini topish etarli bo'lmasligi mumkin. Shuni ham ta'kidlash joizki, uzoqdagi kuzatuvchi vakuumdagi Kerr qora o'rasini kichikroq aylanish parametriga ega bo'lgan va qorong'u modda maydonida joylashgan qora o'radan hamda kattaroq aylanish parametriga ega magnitlangan qora o'radan butkul farqlay olmaydi. Shuning uchun, dissertatsiyadagi ushbu nazariy tadqiqotlar astrofizik kuzatuvlarni tushuntirishda qora tuynuklarga muqobil modellarning haqiqiylikini cheklashga imkon beradi. Shuningdek, qora moddning o'ta massiv qora o'ralar atrofidagi taqsimotini yuqori va quyi chegaralarini nazariy tahlili oraliq modalar bilan o'zaro ta'sirlashib olisdagi gravitatsion ob'ektlardan keladigan signallar orqali kuzatuv ma'lumotlarini ishlab chiqishda qorong'u modda maydonining tabiati va dinamikasini tahlil qilish va tekshirish uchun ishlatilishi mumkin. Aksial simmetrik magnitlangan qora o'rasidan ajralgan energiyaning samaradorligi bo'yicha olingan natijalar faol galaktik yadrolardan ajralib chiqayotgan ulkan energiyaga ega bo'lgan turli ko'rinishdagi oqimlar bilan bog'liq astronomik kuzatuv ma'lumotlarini tahlil qilishda foydali bo'lishi mumkin. Yuqori o'lchamdagi qora o'ralarning o'ziga xos xususiyatlarini o'rganish bilan bog'liq natijalar koinotda yuqori o'lchamlardagi aylanadigan qora o'ralar evolyutsiyasini tushuntirish va qabul qilingan model sifatida yangi metodlarni ishlab chiqish uchun ishlatilishi mumkin.

Tadqiqot natijalarining joriy qilinishi. Gravitasion relyativistik nazariyalarida kompakt astrofizik ob'ektlarning evolyutsiyasi va dinamikasini tadqiq qilish asosida:

yuqori o'lchamli ($D > 4$) Eynshteyn va sof Gauss-Bonnet aylanadigan qora o'ralar atrofidagi aylana orbitalar va qora o'ra hosil bo'lish jarayonlari bo'yicha

olingan nazariy tadqiqot natijalari va usullari Hindistondagi Universitetlararo Astronomiya va Astrofizika markazining grant qo'mitasi dasturlari doirasida (Hindistondagi Universitetlararo Astronomiya va Astrofizika markazi grant qo'mitasining 2022 yil 25 noyabrdagi ma'lumotnomasi) va bir qator xorijiy mualliflar (Physics of the Dark Universe, Vol. 35, id. 100916, 2022; Physical Review D, Vol. 105, id. 124033, 2022; Classical and Quantum Gravity, Vol. 38, id. 155017, 2021) tomonidan xalqaro ilmiy jurnallarda chop etilgan analitik va sonli hisob-kitoblar orqali 4D EGB gravitatsiyasida aylanadigan va zaryadga ega qora o'ra atrofidagi foton harakati va uning soyasini o'rganish va statik EGB qora o'ralari atrofidagi turg'un chegaraviy orbitalarning xususiyatlarini tahlil qilish uchun qo'llanilgan;

qora o'ralarning yuqori ($D > 4$) va kichik ($2+1$) o'lchamlarda ovirspin va ovircharj jarayonlari bo'yicha olingan ilmiy natijalar turli gravitatsiya modellarida qora o'ra gorizontining barqarorligini tekshirish bilan bog'liq bo'lgan turli modellarni ishlab chiqishda bir qator xorijiy tadqiqotchilar (Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 077, 2022; Physical Review Research, Vol. 4, id. 023031, 2022; The European Physical Journal C, Vol. 81, id. 1131, 2021; Physics of the Dark Universe, Vol. 32, id. 100831, 2021; Journal of High Energy Physics, Vol. 2021, id. 45, 2021; The European Physical Journal C, Vol. 81, id. 49, 2021) tomonidan foydalanilgan. Dissertatsiyada olingan natijalarning qo'llanilishi gravitatsiyaning boshqa modellarida qora o'ra gorizontining stabilligini tekshirishning fundamental nazariyalarini ishlab chiqish imkonini beradi;

ideal qorong'u moddaning tashqi magnit maydonda joylashgan statik qora o'ra atrofidagi zarralar harakatiga ta'siri va ideal qorong'u modda va kosmologik doimiyning birgalikdagi ta'sirini o'rganish bo'yicha olingan tadqiqot natijalari kvazperiodik tebranishlar manbai sifatida muntazam minimal bo'lmagan magnit qora o'ralarni, kichik zaryadlangan qorong'u modda komponentalarini qora o'ra soyasi orqali va xalqaro ilmiy jurnallarda chop etilgan gravitatsiyaning turli modellarida ideal qorong'u modda maydonida joylashgan RN-AdS qora o'ralarning Joul-Tomson kengayish formalizmini ishlab chiqishda bir qator xorijiy tadqiqotchilar (Physics Letters B, Vol. 829, id. 137031, 2022; Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 077, 2022; Journal of Cosmology and Astroparticle Physics, Vol. 2021, id. 012, 2021; Physical Review D, Vol. 104, id. 084015, 2021; Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 043, 2022; Universe, Vol. 8, id. 369, 2022; Physical Review D, Vol. 103, id. 104070, 2021; Communications in Theoretical Physics, Vol. 73, id. 095403, 2021; The European Physical Journal C, Vol. 81, id. 269, 2021) tomonidan foydalanilgan;

aksial simmetrik magnitlangan qora o'ra fazo-vaqt geometriyasining o'ziga xos xususiyatlari va uning magnit maydonini astrofizik hodisalar va energiya ajralishi samaradorligiga ta'sirini aniqlashga bag'ishlangan nazariy natijalari Meksikadagi Michoakana Universitetining fizika va matematika institutining CF-MG-2558591 FORDECYT-PRONACES CONACYT raqamli granti doirasida

(Meksikdagi Michoakana Universitetining fizika va matematika instituti xati ilova qilinadi) va zaryadlangan zarrachalar dinamikasini nazariy jihatdan o'rganishni ishlab chiqishda kavant jihatdan statik qora o'ralar va magnitlangan Kerr va RN fazo vaqtlaridagi Faraday aylanishining gravitatsion analogi va boshqa sohalarda bir qator xorijiy tadqiqotchilar (Physical Review D, Vol. 105, id. 064072, 2022; International Journal of Modern Physics A, Vol. 37, id. 2250144, 2022; The European Physical Journal Plus, Vol. 137, id. 645, 2022; Universe, Vol. 8, id. 571, 2022; The European Physical Journal Plus, Vol. 136, id. 1032, 2021; The European Physical Journal C, Vol. 81, id. 983, 2021; Physical Review D, Vol. 104, id. 064016, 2021; Galaxies, Vol. 9, issue 4, id. 71, 2021; Galaxies, Vol. 9, id. 63, 2021) tomonidan ishlatilgan.

Tadqiqot natijalarining aprobasiyasi. Mazkur tadqiqot 3 ta halqaro va respublika ilmiy anjumanlarida muhokamadan o'tkazilgan.

Tadqiqot natijalarining e'lon qilinishi. Dissertasiya mavzusi bo'yicha jami 23 ta ilmiy ishlar chop qilingan, shulardan O'zbekiston Respublikasi Oliy attestasiya komissiyaning doktorlik dissertasiyalari asosiy ilmiy natijalarini chop etishga tavsiya etilgan ilmiy nashrlarda 20 ta ilmiy maqola, shulardan 19 tasi xalqaro ilmiy jurnallarda nashr etilgan.

Dissertasiyaning tuzilishi va hajmi. Dissertasiya tarkibi kirish, 4 ta bob, xulosa va foydalanilgan adabiyotlar ro'yxatidan iborat. Dissertasiyaning hajmi 218 betni tashkil etadi.

DISSERTATSIYANING ASOSIY MAZMUNI

Dissertasiyaning kirish qismida ilmiy tadqiqotning dolzarbligi, ahamiyati keltirilgan, maqsadi va vazifalari aniqlangan, ilmiy yangiligi hamda amaliy natijalari ko'rsatilgan, olingan natijalarning ishonchliligi isbotlangan, ularning nazariy va amaliy ahamiyati borasida so'z yuritilgan, tadqiqot natijalari va dissertasiya tuzilishi berilgan.

Dissertatsiyaning birinchi bobi "Yuqori o'lchamlarda qora o'raning shakllanishi va dinamikasi" deb nomlanib, mavjud tortishish markazida materiyaning to'planishini hisobga olgan holda qora o'ra hosil bo'lish jarayonlarini ko'rsatishga va yuqori o'lchamlarda aylanuvchi qora o'ralar atrofida chegaraviy yoki ichki barqaror aylana orbitalarning (IBAO) mavjud yoki yo'qligini ko'rsatishga bag'ishlangan.

Yuqori o'lchamlarda aylanadigan qora o'rani tavsiflovchi Myers-Perry yechimi mavjud bo'lib, uning fazo vaqti qo'yidagi ko'rinishda yoziladi

$$ds^2 = -dt^2 + r^2 d\beta^2 + \sum_{i=1}^n (r^2 + a_i^2)(d\mu_i^2 + \mu_i^2 d\phi_i^2) + \frac{\mu r}{\Pi F} (dt + \sum_{i=1}^n a_i \mu_i^2 d\phi_i)^2 + \frac{\Pi F}{\Delta} dr^2, \quad (1)$$

bu erda

$$F = 1 - \sum_{i=1}^n \frac{a_i^2 \mu_i^2}{r^2 + a_i^2}, \quad \Pi = \prod_{i=1}^n (r^2 + a_i^2), \quad \Delta = \Pi - 2\mu r^{2n-D+3}. \quad (2)$$

μ va a_i qora o'raning massasi va aylanish parameterlari, hamda μ_i va β parameterlar qo'yidagi ifodalar orqali bog'langan,

$$\sum_{i=1}^n \mu_i^2 + \beta^2 = 1, \text{ va } \sum_{i=1}^n \mu_i^2 = 1. \quad (3)$$

(3) tenglama mos ravishda juft $D = 2n + 2$ va toq $D = 2n + 1$ o'lchamlar uchun yozilgan va uning ikkinchi ifodasi $\beta = 0$ bo'lganda har doim o'rinli bo'ladi. Shuni ham ta'kidlash joizki, μ_i yo'nalish kosinuslari hisoblanib, misol uchun μ_1 va μ_2 $D = 5,6$ o'lchamli fazolarda qo'yidagi ifodalar orqali beriladi

$$\mu_1 = \sin\theta \quad \text{va} \quad \mu_2 = \cos\theta, \quad (4)$$

va

$$\mu_1 = \sin\theta, \quad \mu_2 = \cos\theta \sin\chi \quad \text{va} \quad \beta = \cos\theta \cos\chi. \quad (5)$$

Yuqori o'lchamli fazolarda, qora o'ra bir nechta aylanish parametriga ega bo'lishi mumkin, ya'ni yuqori o'lchamlarda qora o'ra ega bo'lish mumkin bo'lgan maximum aylanishlar soni $n = [(D - 1)/2]$ ga teng bo'lishi mumkin. Misol uchun, qora o'ra $D = 5,6$ o'lchamli fazolarda $n = 2$ aylanish parametriga ega bo'ladi.

Xususan, 5 va 6 o'lchamli fazolarni ko'rib chiqamiz va (i) nolga teng bo'lmagan aylanish momenti uchun effektiv potensial, $V_{eff} > 1$, har doim bajarilishini va (ii) u faqat maksimumga ega bo'lishini va shuning uchun hech qanday chagaraviy va barqaror aylana orbitalari hosil bo'lishi mumkin emasligini ko'rsatamiz. Vaqtsimon zarralarning qo'ra o'ra atrofidagi geodesik harakat qonuniyatlaridan foydalanib, effektiv potensialning umumiy ifodasini yozib olamiz. Natijada, bitta aylanish parametriga ega bo'lgan 5 va 6 olchamli qora o'raning ekvatorial teksligida harakatlanuvchi zarralar uchun effektiv potensail qo'yidagi ifoda orqali beriladi

$$V_{eff}(r) = -\frac{g_{t\phi}}{g_{\phi\phi}} \mathcal{L} + \sqrt{\frac{\Delta}{g_{\phi\phi}} \left(1 + \frac{\mathcal{L}^2}{g_{\phi\phi}}\right)}. \quad (6)$$

Bu yerda qo'yidagi ifodalardan foydalandik, ya'ni $\mathcal{E} = E/m$, $\mathcal{L} = L/m$ va $m^2 = 1$. (6) ifodadan $D = 5,6$ olchamli fazolar uchun effektiv potensial $V_{eff}(r)$ qo'yidagi ko'rinishda ifodalanadi:

$$V_{eff}^{5D}(r) = \frac{a\mu\mathcal{L}}{r^4 + (r^2 + \mu)a^2} + \frac{r(r^4 + (r^2 + \mu)a^2 + r^2\mathcal{L}^2)^{1/2}}{r^4 + (r^2 + \mu)a^2} \times (r^2 - \mu + a^2)^{1/2}, \quad (7)$$

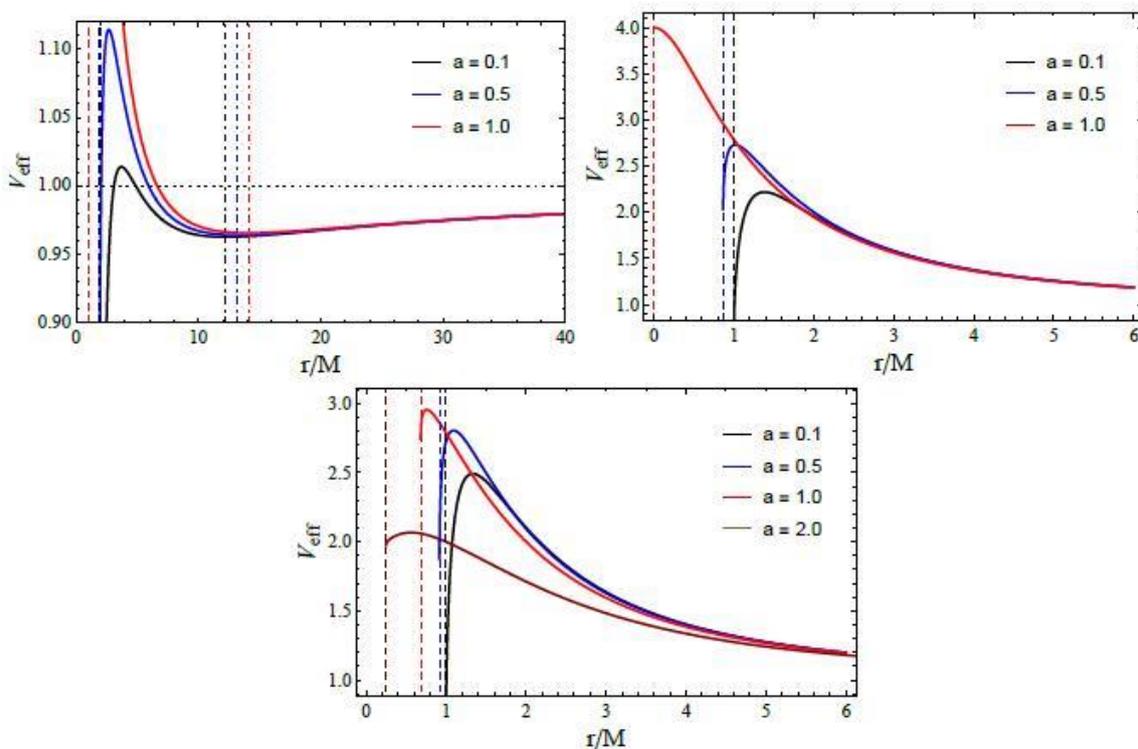
$$V_{eff}^{6D}(r) = \frac{a\mu\mathcal{L}}{r^5 + (r^3 + \mu)a^2} + \frac{r(r^5 + (r^3 + \mu)a^2 + r^3\mathcal{L}^2)^{1/2}}{r^5 + (r^3 + \mu)a^2} \times (r^3 - \mu + a^2r)^{1/2}. \quad (8)$$

Katta masofalarda r , yuqoridagi ifodalar qo'yidagi ko'rinishga ega bo'ladi

$$V_{eff}^{5D}(r \rightarrow r_\infty) \sim 1 + \frac{(\mathcal{L}^2 - \mu)}{2r^2} + \mathcal{O}\left(\frac{1}{r^4}\right), \quad (9)$$

$$V_{eff}^{6D}(r \rightarrow r_\infty) \sim 1 + \frac{\mathcal{L}^2}{2r^2} - \frac{\mu}{2r^3} + \mathcal{O}\left(\frac{1}{r^4}\right),$$

bundan ko'rinadiki $D > 4$ holatda itaruvchi markazdan qochma komponenta gravitatsion tortishishdan har doim ustun bo'ladi. $\mathcal{L} = 0$ holatda, qo'ra o'ra aylanish parametrining ta'siri yo'qolishi sababli faqat tortishuvchi komponenta har doim ustivor bo'ladi.



1-rasm. $L = 4$ uchun effektiv potensial grafiklari: Yuqoridan 1, 2, va 3-grafiklar mos ravishda $D = 4, 5, 6$ o'lchamli holatlarni o'zida aks ettiradi. Vertikal uzun chiziqlar hodisalar gorizontini, vertikal nuqtali chiziqlar esa V_{eff} ning minimum vaziyatini ko'rsatadi.

1-rasmdan ma'lum bo'ldiki, $V_{eff} \geq 1$ har doim o'rinli bo'ladi. Har ikki $D = 5, 6$ haolatda ham $V_{eff} = 1$ cheksizlikda o'rinli bo'ladi, va u r kamayishi bilan oshib boradi va gorizontga qulashdan oldin o'zining maximumiga intiladi. Shuni alohida ta'kidlash joizki, effektiv potensial uchun gorizont yaqinida $V_{eff} \geq 1$ har doim o'rinli bo'ladi. Bu esa 4 o'lchamli fazoga nisbatan $V_{eff} \leq 1$ asosiy farq hisoblanadi. Bundan tashqari, $D = 6$ holatda $a \rightarrow \infty$ intilishi bilan, effektiv potensial ham $V_{eff} \rightarrow 1$ intiladi r ning barcha qiymatida. Shuning uchun a ning oshishi bilan maximum avval ko'tariladi va u o'zining $a \sim 1.3$ qiymatiga yetganida pastga qarab tushushni boshaydi. Shunday qilib, effektiv potensial faqat o'zining extrimumiga erishadi, yani maximumiga (1-rasmga qarang). Bu esa shuni anglatadiki, ya'ni u yerda hech qanday chegaraviy va barqaror aylana orbitalar paydo bo'lmasligini ko'rsatadi. Bu yuqori o'lchamdagi aylanuvchi qora o'ralar uchun zarrachalar harakatining o'ziga xos xususiyati hisoblanadi.

1-rasmda effektiv potensialning $\mathcal{L} = 4$ va $D = 4, 5, 6$ uchun grafiklari olingan. Aylanish momenti nol bo'lganda, potensial katta masofalarda r effektiv potensial $1 - \mu/2r^{D-3}$ ko'rinishga ega bo'ladi, va shuning uchun har doim ≤ 1 bo'lishligi o'rinli bo'ladi. Ya'ni, qora o'ra aylanish parametrining ta'siri yo'qoladi va faqat

massasining ta'sir effekti qoladi. Demak, $D > 4$ da effektiv potensial gorizont yaqinadan boshqa joyda har doim bir birlikdan katta va faqat maksimumga ega bo'ladi. Bu esa barqaror aylana orbitalarni tutib turadigan yetarlicha potensial mavjud bo'lmasligini anglatadi. Shuning uchun, yuqori o'lchamlarda chagaraviy va barqaror aylana orbitalarning mavjud bo'lmasligi hayron qolarli hodisa bo'lmaydi. Bu esa yuqori o'lchamlarda akkretsiyaning jarayoniga o'z tasirini ko'rsatadi. Akkretsiya jarayoni akkretsiyon disk orqali amalga oshiriladi, bu jarayon esa sodir bo'lmaydi, chunki qora o'ra atrofida chagaraviy va barqaror aylana orbitalar mavjud emas. Bu yuqori o'lchamdagi aylanuvchi va aylanmaydigan qora o'ralar uchun ham amal qiladi. Akkretsiyon diskda dissipativ o'zaro ta'sirlar natijasida zarralar aylanish momentini yo'qotib qora o'ra markazi tomon $L < L_{ISCO}$ bilan spiral harakatini davom ettirishi mumkin. Yuqori o'lchamlarda esa akkretsiyon disk yuzaga kelishligi uchun barqaror orbitalar mavjud bo'lmaydi, provardida akkretsiya jarayoni vujudga kelmaydi. Shuning uchun, akkretsiya jarayoni yuqori o'lchamlarda aylanadigan qora o'ra hosil bo'lishida hech qanday rol o'ynamaydi.

Dissertatsiyaning ikkinchi bobi "Qora o'ra gorizontining barqarorligini kichik $D < 4$ va yuqori $D > 4$ o'lchamlarda tekshirish" deb nomlanib, u kosmik senzura hodisasini yuqori $D > 4$ va kichik $D < 4$ o'lchamlarda zarraning chiziqli va nochiziqli ta'sirlari uchun ovespin va overcharj jarayonlarini o'rganish orqali unumiy formalizimini rivojlantirishga bag'ishlangan.

Eynshteyn va Eynshteyn-Gauss-Bonnet gravitatsiya nazariyalarida Martines, Teitelboim va Zanelli (MTZ) tomonidan olingan (2+1) o'lchovli zaryadlangan qora o'ra yechimi uchun kosmik senzura hodisasini mavjudlik shartini tekshiramiz. Bu uchun, Einstein-Hilbert-Maksvel tas'sir integrali qo'yidagi ko'rnishda bo'ladi:

$$S = \int d^3x \sqrt{-g} \left(\frac{R-2\Lambda}{16\pi} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right). \quad (10)$$

Bu eyerda $F_{\mu\nu}$ elektromagnit maydon tensori, R esa fazo vaqtining skalyar egriligi hisoblanadi. Zaryadlangan (2+1) o'lchamli MTZ qora o'ra yechimi qo'yidagi ko'rinishda yoziladi

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2, \quad (11)$$

bu eyerda

$$f(r) = r^2 - M - \left(\frac{Q}{2}\right)^2 \ln(r^2), \quad (12)$$

M va Q esa qora o'raning massasi va elektr zaryadini tasvirlaydi. $f(r)$ funksiya $r_{\min} = Q/2$ da minimumga ega funksiya hisoblanadi. Bu funksiya o'zining minimumidagi qiymati esa qo'yidagi ifoda bilan beriladi

$$f(r_{\min}) = -M + \left(\frac{Q}{2}\right)^2 \left[1 - \ln\left(\frac{Q}{2}\right)^2\right]. \quad (13)$$

Yuqoridagi funksiya uchun qora o'ra fazo vaqtini xarakterlaydigan uchta holat bo'lishi mumkin: Agar $f(r_{\min}) = f(Q/2) < 0$ bo'lsa, $f(r)$ funksiyaning ikkita ildizi mavjud bo'lib qora o'raning tashqi r_+ va ichki r_- , gorizontlariga mos keladi. Agar $f(r_{\min}) = f(Q/2) = 0$ bo'lsa, u holda uning ikkita yechimi bir xil bo'ladi va bu extremal qora o'raga mos keladi. Agar $f(r_{\min}) = f(Q/2) > 0$

o'rinli bo'lsa, $f(r)$ funksiyaning haqiqiy yechimi bo'lmaydi, bu esa ochiq singulyar ob'ektga mos keladi. Qora o'ralarning extremal holati $f(Q/2) = 0$ ga to'g'ri keladi. $f(r_+) = 0$ ligidan, extremal qora o'ra uchun gorizont $r_+ = Q/2$ ga teng bo'ladi. Qora o'ra yechimi uchun qo'yidagi $f(r_{\min}) \leq 0$ shart talab qilinadi, bundan qo'yidagi ifoda kelib chiqadi

$$\delta \equiv M - \left(\frac{Q}{2}\right)^2 \left[1 - \ln\left(\frac{Q}{2}\right)^2\right] \geq 0. \quad (14)$$

(14) ifodadagi $(Q/2)^2[1 - \ln(Q/2)^2]$ funksiya zaryadning $Q = 0$ va $(Q/2)^2 = e$ qiymatlarida mavjud bo'lmaydi, lekin $(Q/2)^2 = 1$ (yoki $Q = 2$) qiymatida maximumga ega bo'ladi. Shuning uchun, $M > 1$ da, r_+ va r_- gorizonlari bo'lgan odatdagi qora o'raning mavjud bo'lishi uchun δ funksiya har doim noldan katta bo'ladi.

Extremal va extremal bo'lmagan MTZ qo'ra o'rasining gorizontini buzilishini ko'rsatdik. Bunga ishonch hosil qilish maqsadida, qora o'ra gorizontining stabilligini zaralarning nochiziqli ta'sirlari uchun ham tekshirib ko'ramiz. Ya'ni bu bobda, zarralarning ikkinchi tartibli perturbatsiyalarini e'tiborga olib MTZ qora o'ra goizontining stabilligini overcharging jarayoni orqali tekshiramiz. Yuqorida keltirilgan (14) ifodani yana bir marta yozib olamiz,

$$\delta \equiv M - \left(\frac{Q}{2}\right)^2 \left[1 - \ln\left(\frac{Q}{2}\right)^2\right].$$

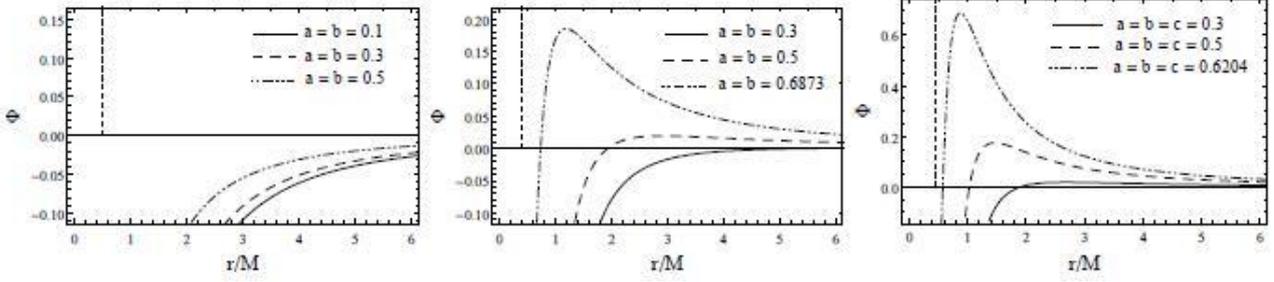
$\delta > 0$ holatlar qora o'ra yechimini o'zida aks ettiradi, lekin $\delta < 0$ holatlar ochiq singulyar (gorizontsiz) ob'ektlarga mos keladi. $\delta(\lambda)$ funksiyani hatto ikkinch tartibli $\delta^2 E$ va $\delta^2 Q$ ta'sirlarni e'tiborga olganda ham manfiy bo'lishligini topdik. Shuning uchun, ikkinchi tartibli perturbatsiyalar ham extremal bo'lmagan qora o'ra gorizontining stabilligini saqlay olmaydi, yani uning gorizontini buzilishi muqarrardir. Bu esa (2+1) o'lchamli MTZ qora o'rasining tabiatini yaxhiroq o'rganishga imkon beradi, chunki uning gorizonti 4 o'lchamli fazodagi qora o'ra gorizontiga solishtirganda stabil emas. Bu $D < 4$ o'lchamdagi zaryadlangan MTZ qora o'rasinig o'ziga xos jihatidir. Yuqoridagi tahlillarni EGB gravitatsiya nazariyasidagi (2 + 1) o'lchamli BTZ qora o'rasi uchun ham tekshirdik. Tahlillar natijasi shuni ko'rsatdiki, extremal bo'lmagan BTZ qora o'ra gorizonti (2+1) MTZ qo'ra o'rasiga o'xshab stabil bo'lmaydi, ya'ni kosmik senzura hodisasini buzilishiga olib keladi.

Keyingi bosqichda kosmik senzura hodisasini yuqori o'chamli, $D > 4$, ($n - 1$) va n ta aylanish parametriga ega bo'lgan qora o'ralar uchun ham tekshirib ko'rdik. Ma'lum bo'lishicha, berilgan D o'lchamda ($n - 1$) ta aylanish parametriga ega bo'lgan qo'ra o'ra maximum aylanish soniga $n = [(D - 1)/2]$ ega bo'lgan qora o'ra tabiatidan tubdan farq qiladi. Bu holatni alodiha ko'rib chiqamiz. Yuqori o'lchamli aylanuvchi Myers-Perry qora o'rasining mos ravishda toq $D = 2n+1$ va juft $D = 2n+2$ o'lchamlardagi fazo vaqti elementlari (1) ifoda orqali beriladi. Qora o'raning gorizont radiusi toq va juft o'lchamlarda $\Delta = 0$ tenglama yordamida qo'yidagicha topiladi:

$$(r^2 + a_1^2) \dots (r^2 + a_i^2) - \mu r^2 = 0, \quad (15)$$

va

$$(r^2 + a_1^2) \dots (r^2 + a_l^2) - \mu r = 0. \quad (16)$$



2-rasm. Chapdan o'nga: $\Phi(r)$ potensialning $D=5,6,7$ uchun r/M radial bo'lganishi chizilgan. Barcha rasmlarda vertikal uzun chiziq aylanish parametrining extremalga yaqin bo'lgan qiymatlari uchun gorizont radiusini ko'rsatadi.

n aylanishga ega bo'lgan qora o'ra uchun uning effektiv gravitatsion potentsiali qo'yidagi ifoda bilan beriladi,

$$\Phi(r) \approx \frac{\Delta}{r^2} - 1 = \frac{(r^2 + a^2) \dots (r^2 + a_n^2)}{r^{2n}} - \frac{\mu}{r^{D-3}} - 1. \quad (17)$$

2-rasm $D = 5,6,7$ uchun effektiv gravitatsion potensial $\Phi(r)$ va uning birinchi tartibli hosilasini ifoda etadi. Rasmdan ma'lumki $D = 5$ uchun natijaviy kuch har doim tortishuvchi tabiatga ega, lekin r/M uzoq masofalarda $D = 6,7$ uchun itaruvchi tabiatga ega bo'lib qoladi. Bu barcha yuqori ≥ 6 o'lchamlarda bir xil bo'ladi. Shunday bo'lsada gorizontga yaqin joyda natijalovchi kuch tortishuvchi bo'lib qoladi. Buning sababi gorizontning o'zi $r/M < 1$ da hosil bo'ladi va unga yaqin joyda massa hisobiga tortishuvchi had $1/r^{D-3}$ har doim itarishuvchi haddan $1/r^2$ ustun bo'ldi.

Dissertatsiyada aniq hisob-kitoblar asosida olti o'lchamli ikkita aylanish parametriga ega qora o'ra uchun ovirspin jarayoni bajarilmasligi ko'rsatildi. Ya'ni, bu barcha $D \geq 6$ o'lchamlarda naximum aylanish parametriga ega bo'lgan qora o'ralar bir xil bo'ladi. Natijada qo'yidagilarni aytishimiz mumkin: *Teorema I:* Berilgan o'lchamdagi qora o'raning aylanish parametrlaridan biri nolga teng bo'lib qolsa (ya'ni $(n - 1)$ uchun) overspin jarayoni hech qachon sodir bo'lmaydi va natijada har doim kosmik senzura hodisasi o'rinli bo'ladi. *Teorema II:* $D > 5$ o'lchamlarda qora o'ra uchun overspin jarayoni hech qachon bajarilmaydi va shuning uchun har doim kosmik senzura hodisasi bajariladi.

Dissertatsiyaning uchunchi bobi "Ideal qorong'u moddaning zarralar harakati va qora o'ralarning dinamikasiga ta'siri" deb nomlanib, idal qorong'u moddaning turli gravitatsiya nazariyalarida zarralar va qora o'ralar dinamikasiga ta'sirini o'rganishga va uning Sgr A va M87 galaktikalari markazida joylashgan o'ta massiv qora o'ra atrofidagi yuqori va qo'yi chegra qiymatlarini topishga bag'ishlangan.

Idal qorong'u modda maydonida jouylashgan statik va sferik juhatdan simmetrik bo'lgan qora o'ra fazo vaqti Schwarzschilda kordinatalar (t, r, θ, φ) sistemasida qo'yidagicha beriladi

$$ds^2 = -F(r)dt^2 + F(r)^{-1}dr^2 + r^2d\Omega^2, \quad (18)$$

bu yerda $d\Omega^2$ ikki o'lchamli sfera elementini va $F(r)$ esa qo'yidagi funksiyini ifodalaydi

$$F(r) = \left(1 - \frac{2M}{r} + \frac{\lambda}{r} \log \frac{r}{|\lambda|}\right), \quad (19)$$

bu erda M qo'ra ora massasi va λ esa qorong'u moddaning zichligi va bosimiga bo'g'liq bo'lgan parametr. $\lambda \neq 0$ holat uchun qorong'u modda energiya-moment tenzori $T_\nu^\mu = \text{diag}(-\rho, p_r, p_\theta, p_\phi)$ uning zichligi va tangensial bosimlari uchun qo'yidagi ifoda orqali beriladi

$$\rho = -p_r = \frac{\lambda}{8\pi r^3}, \quad p_\theta = p_\phi = \frac{\lambda}{16\pi r^3}. \quad (20)$$

$\lambda \ll 1$ hollarda ichki barqaror aylana orbita (IBAO) r_i va foton orbitasi r_{ph} analitik topilgan

$$r_i \approx 6M + \left[4 - 3 \log \left(\frac{6M}{\lambda}\right)\right] \lambda + O(\lambda^2), \quad (21)$$

$$r_{ph} \approx 3M + \frac{1}{2} \left[1 - \log \left(\frac{27}{8}\right)\right] \lambda + O(\lambda^2). \quad (22)$$

Maksvell tenlamalarini yechib ideal qorong'u modda maydoni uchun elektromagnit maydonning 4-potensialining kovariant komponentlari quyidagicha topilgan

$$A_t = A_r = A_\theta = 0, \\ A_\varphi = \frac{B}{2} r^2 \left[1 + \frac{\lambda}{r} \left(1 + \log \frac{M}{r}\right) + O(\lambda^2)\right] \sin^2 \theta.$$

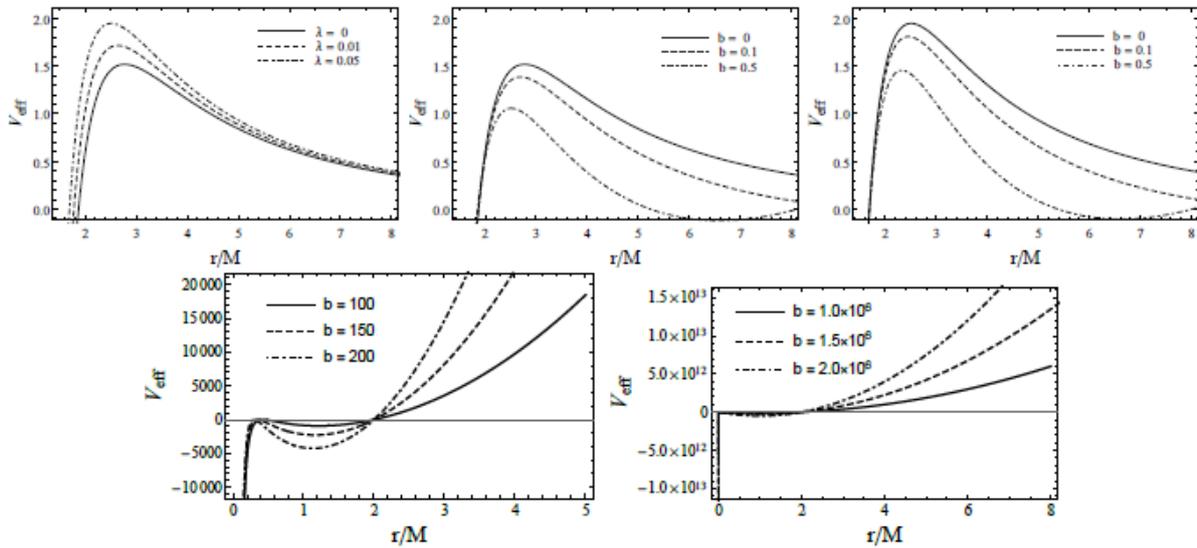
Zaryadlangan sinov zarra uchun effective potensial qo'yidagicha topilgan

$$V_{eff} = F(r) \left(1 + \frac{\left[\mathcal{L} - \frac{b}{M} \left(1 + \frac{\lambda}{r} \left(1 + \log \frac{M}{r}\right)\right) r^2\right]^2}{r^2}\right), \quad (23)$$

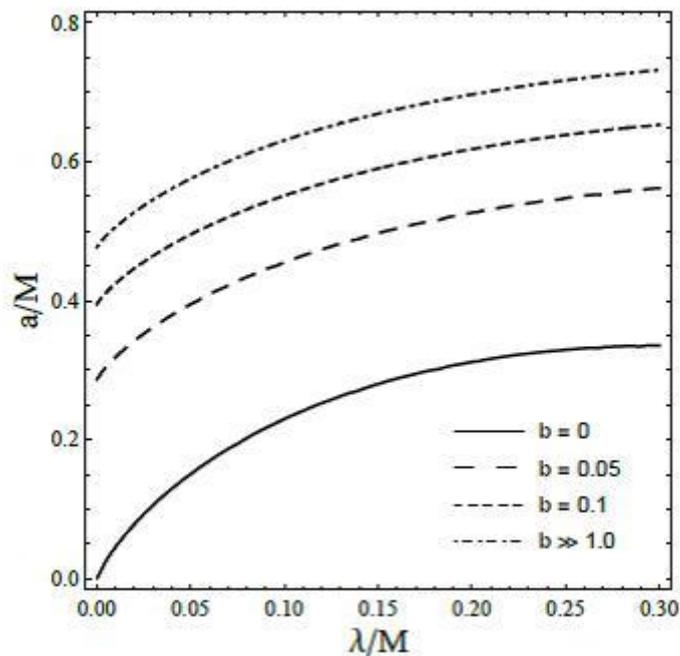
bu yerda harakat doimiylarini qo'yidagicha $\mathcal{E} = E/m$, $\mathcal{L} = L/m$ ifodalab oldik. Zaryadlangan zarralarni harakatiga ta'sirini baholaydigan magnit parametri $b = qBMG/mc^4$ deb olindi.

3 rasmda λ va b turli qiymatlari uchun V_{eff} ning radial bogliqligi tasvirlangan. Qorong'u moddaning mavjudligi ($\lambda > 0$) magnit maydonga ($b > 0$) nisbatan teskari ta'sirga ega ekanligini ko'rish mumkin. Potensialning kuchi nuqtai nazaridan qaraganda, bu ikki λ va b parametrlarning aniq qiymatlari uchun ma'lum bir radiusda ularning ta'sirlari o'zaro muvozanatlashadi. Shu bilan birga, magnit parametrining ishorsiga qaramay IBAO radiusi Schwarzschildga solishtirganda

kamayadi. Effectiv potensial b ning realistik qiymatlari uchun 3-rasmning pastki qatorida tasvirlangan.



3-rasm. Tashqi magnit va ideal qorong'u modda maydonlarida joylashgan qora o'ra atrofida massiv zarralar uchun effectiv potensialning radial bog'liqligi aks etgan. Yuqori qator, chap panel: V_{eff} $b=0$ va λ turli qiymatlari uchun ko'rsatilgan. Yuqori qator, o'rta panel: V_{eff} $\lambda=0$ va b ning turli qiymatlari uchun ko'rsatilgan. Yuqori qator, o'ng panel: V_{eff} $\lambda = 0,05$ holatda va b ning turli qiymatlari uchun ko'rsatilgan. Pastki qatordagi ikkita panelda $\lambda = 0,05$ deb olib $b \gg 1$ qiymatlarini hisobga olganda V_{eff} ga qanday ta'sir qilishi tasvirlangan.



4-rasm. Kerr va ideal qorong'i modda holatlari uchun IBAO joylashuvining degeneratsiyasi tasvirlangan. Kerr geometriyasidagi IBAO radiusi ideal qorong'u modda geometriyasidagi IBAO bilan bir xil bo'ladigan holatlar uchun aylanish a/M parametri qiymatlarining λ ga bog'liqligi tasvirlangan.

Kuzatuv nuqtai nazaridan qaraganda, olisdagi kuzatuvchilar markaziy ob'ekt atrofida aylanib yuruvchi akkretsiya diskidagi gaz chiqaradigan elektromagnit nurlanishlarni tahlil qilish orqali, ikkita fazo vaqt geometriyasini farqlay olmaydi. 4-rasmga e'tibor beradigan bo'lsak, qorong'u modda va magnit maydonning birgalikdagi o'zaro ta'siri qora o'ra aylanish parametrining $a/M \approx 0.75 - 0.8$ gacha bo'ladigan ta'sirni berishi mumkin, lekin qorong'u moddaning oz'i $a/M \approx 0.35$ gacha aylanish parametriga taqlid qilishi mumkin. Bu shuni ko'rsatadiki, qora o'ra nomzodining aylanish parametrini o'lchash uning atrofida qorong'u modda mavjudligi bilan 30% gacha va agar tashqi magnit maydon mavjud bo'lsa, undan ham ko'proq ta'sir qilishi mumkin.

Astrofizik qora o'ralarga qo'llash masalasiga kelganda, yuqoridagi dalillar shuni ko'rsatadiki, tez aylanadigan qora o'ra nomzodlarini aniqlashda qorong'u modda mavjudligida sekin aylanuvchi qora o'ralar ham bo'lishligi e'toborga olinishi mumkin. Shuni ham ta'kidlash joizki, galaktikalar markazidagi qorong'u moddaning xarakterli zichligi to'g'risida aniq ma'lumotga ega bo'lmaganligimiz uchun uning realistik qiymatini o'lchay olmaymiz. Biroq, biz markaziy ob'ektdan bir necha parsek masofada qorong'u moddaning taxminiy miqdorini hisobga olishimiz mumkin. Raqamli simulyatsiyalar va kichik massali galaktikalarning kuzatuvlaridan kelib chiqadigan natijalar bo'yicha o'tkazilgan tadqiqotlarga ko'ra kuzatuvlardan olingan qorong'u modda zichligi $\rho \sim (10^{-2} - 10^{-1})M_{\odot}/pc^3$ oralikda bo'ladi. Bu natijaga asoslanib, dissertatsiyada keltirilgan model bo'yicha qorong'u moddaning λ mos qiymati Sgr A* uchun $\lambda \sim (10^{-21} - 10^{-20})$ va M87 galaktikasi uchun esa $\lambda \sim (10^{-12} - 10^{-11})$ ga tengligi topildi.

Dissetatsiyaning to'rtinchi bobi "Aksial simmetrik magnitlangan Reissner-Nordström qora o'rasining fazo vaqtida Penrouz jarayonining energiya samaradorligi" deb nomlanib, aksial simmetrik magnitlangan Reissner-Nordström qora o'ra fazo-vaqtining geometriyasini hamda o'ziga xos xususiyatlarini o'rganishga va Penrouz jarayoni orqali neytral va zaryadli zarralar uchun uning magnit maydonini energiya ajralish samaradorligiga ta'sirini o'rganishga bag'ishlangan.

Aksial simmetrik magnitlangan Reissner-Nordström qora o'ra fazo-vaqti Schwarzschilda kordinatalar (t, r, θ, ϕ) sistemasida qo'yidagicha yoziladi

$$ds^2 = H (-Fdt^2 + F^{-1} dr^2 + r^2 d\theta^2) + H^{-1} r^2 \sin^2 \theta \times (d\phi - \omega dt)^2, \quad (24)$$

bu yerda

$$F = 1 - \frac{2M}{r} + \frac{Q^2}{r^2}, \quad (25)$$

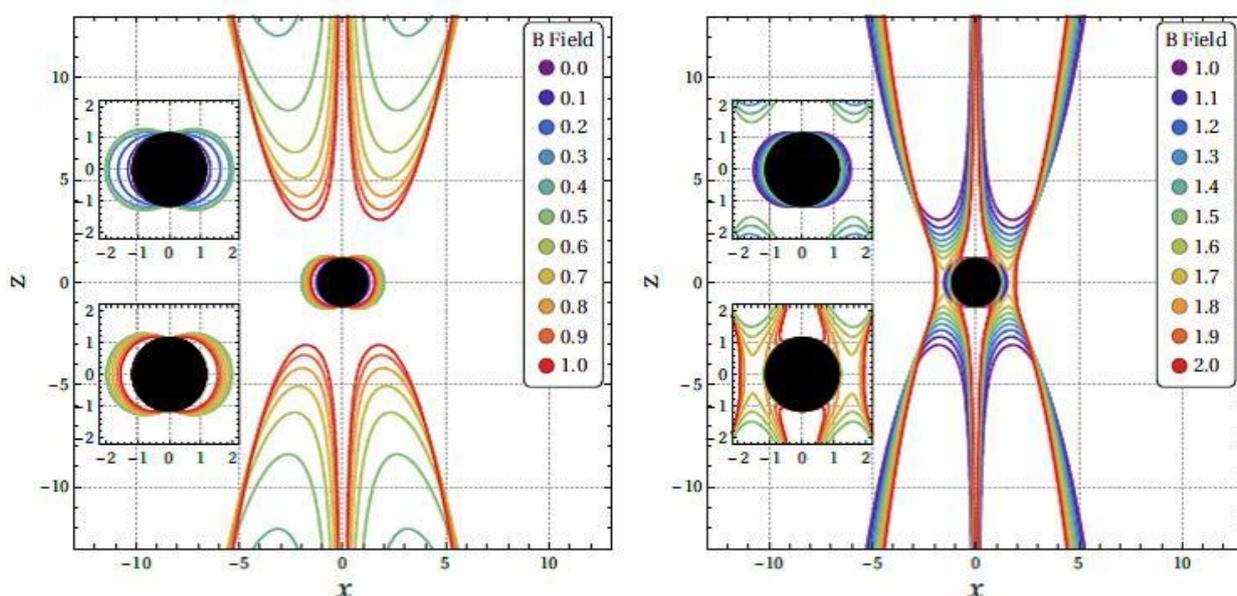
$$H = 1 + \frac{1}{2} B^2 (r^2 \sin^2 \theta + 3Q^2 \cos^2 \theta) + \frac{1}{16} B^4 (r^2 \sin^2 \theta + Q^2 \cos^2 \theta)^2, \quad (26)$$

$$\omega = -\frac{2QB}{r} + \frac{1}{2} QB^3 r (1 + F \cos^2 \theta), \quad (27)$$

M va Q qora o'ra massasi va zaryadi va B magnit maydon paramtrini ifodalaydi. Yuqorida keltirilgan (18) ifoda $B \rightarrow 0$ da Reissner-Nordström va $B, Q \rightarrow 0$ holatda

Schwarzschildda qora o'ralariga mos keladi. Shuni ham ta'kidlash joizki, magnitlangan qora o'ra yechimi hech qanday aylanishsiz magnit maydon mavjudligi natijasida aksial simmetrik fazo-vaqtini yuzaga keltiradi. Bu esa magnitlangan Reissner-Nordström qora o'rasining o'ziga xos ajoyib xususiyati hisoblanadi.

5-rasmdan ko'rish mumkinki, ergo soha qora o'ra markazidan yetarlicha uzoqlikda z o'qining har ikki manfiy va musbat yo'nalishida hosil bo'lishi mumkin. Shuni ta'kidlash kerakki, ergosoha magnit parametrining kichik qiymatlari uchun qora o'radan ajratilgan va katta qiymatlari uchun qora o'ra bilan birlashgan holatlarda bo'ladi. Keyinchalik B parametrning katta qiymatlari ergosoha hajmini oshishiga olib keladi va natijada Penrouz jarayoni orqali yuqori energiya samaradorligiga erishish mumkin. Bu esa magnitlangan qora o'raning boshqa aksial simmetrik qora o'ralarga solishtirganda o'ziga xos xususiyati hisoblandi.



5-rasm. Magnit maydonining B turli kombinatsiyalari uchun ekstremal aksial simmetrik magnitlangan qora o'raning ergo sohasini $x - z$ tekisligidagi ta'sviri ko'rsatilgan.

Chap panelda magnit maydon 0 dan 0,5 gacha o'zgaradigan qiymatlari uchun yuqori qo'shimcha chizmada kattalashtirilgan holda ko'rsatilgan. Shuningdek, magnit maydon 0,5 dan 1,0 gacha o'zgargan holatlar uchun pastki qismidagi chizmada kattalashtirilgan holda ko'rsatilgan. Shunga o'xshab, o'ng panelda magnit maydon 1.0 dan 1,5 gacha o'zgaradigan qiymatlari uchun yuqori qo'shimcha chizmada kattalashtirilgan holda ko'rsatilgan.

Magnit maydon 1.5 dan 2,0 gacha o'zgaradigan qiymatlari uchun esa pastki qismidagi chizmada kattalashtirilgan holda ko'rsatilgan.

Ma'lumki, zamonaviy astronomik kuzatishlar aktiv yadro galaktikalaridan (AYaG) shamol va oqim shaklida yuqori energiyaga $E \approx 10^{42} - 10^{47}$ erg/s ega bo'lgan oqimlar mavjudligini ko'rsatib kelmoqda. Bu kabi yuqori energiyali oqimlar X-nur, γ -nur va boshqa kuzatuvlar yordamida o'z tasdig'ini topmoqda. Zaryadlangan zarrachalar harakatining AYaGdan chiqadigan bu zarrachalar oqimi

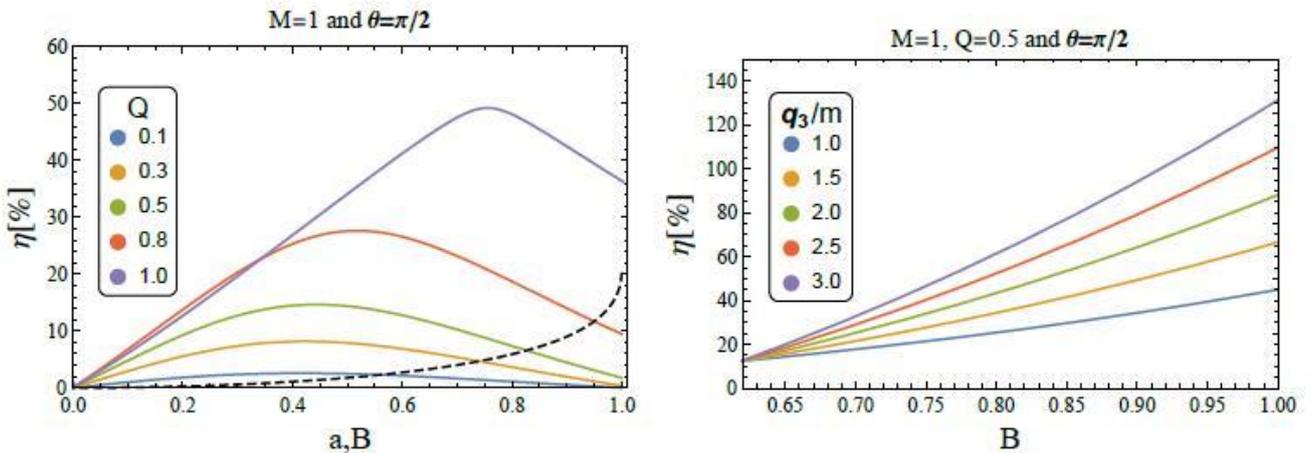
bilan o'ziga xos bog'liqligi mavjud. Shu munosabat bilan, ushbu astrofizik jarayolarni tushuntirish imkonini beradigan Penrouz jarayonini o'rganish zaruriyati tug'iladi. Shunday qilib, qora o'ra atrofidagi ergosohaga zarralar tushishi natijasida nurlanish sifatida olinadigan maksimal energiyani nazarda tutuvchi energiya samaradorligini Penrouz jarayoni orqali tekshiramiz. Neytral $q_3 = 0$ va zaryadlangan $q_3 \neq 0$ zarralar uchun, Penrouz jarayoni orqali energiya samaradorligini mos ravishda quyidagi keltirilgan ifodalar yordamida aniqlash mumkin:

$$\eta|_{q_3=0} = \frac{1}{2(4+B^2(1+\sqrt{1-Q^2})^2)} \times \left[(-8BQ(1+\sqrt{1-Q^2}) \times (4 - B^2(1+\sqrt{1-Q^2})^2) + (4 + B^2(1+\sqrt{1-Q^2})^2)^2)^{1/2} - (4 + B^2(1+\sqrt{1-Q^2})^2) \right], \quad (28)$$

va

$$\eta = \eta|_{q_3=0} - \frac{q_3}{E_1} \left[-\frac{Q}{1+\sqrt{1-Q^2}} + \frac{3}{4}QB^2(1+\sqrt{1-Q^2}) \right]. \quad (29)$$

Masalani soddalashtirish uchun $E_1/m_1 = 1$ deb olamiz. Shunday qilib, qora o'ra atrofida zaraning bo'linish nuqtasida, ayniqsa uning gorizontiga $r = r_+$ juda yaqin joyda $q_3/E_1 = q/m$ ekanligini hisobga olamiz. Lekin, 5-rasmdan yaqqol ko'rinadiki, bo'linish nuqtasining joylashuvi ergosohaning kengayib borishi evaziga qora o'ra gorizontidan yetarlicha katta masofada ham mavjud bo'lishi mumkin. Aniqroq bo'lish uchun zarraning bo'linish nuqtasi qora o'ra gorizontiga yaqin joyda sodir bo'ladi deb olamiz.



6-rasm. Rasmda energiya samaradorligi ekvator tekisligida, $\pi/2$, magnet maydon B ning funktsiyasi sifatida tasvirlangan. Chap panelda energiya samaradorlik qiyatini neytral zarrachali holatda Q ning turli kombinatsiyalari uchun tasvirlangan. O'ng panelda energua samaradorlik qiymatini o'zgarmas $Q=0.5$ holatida q_3/m ning turli kombinatsiyalari uchun tasvirlangan. Chap paneldagi uzoq chiziq aylanuvchi Kerr qora o'rasi uchun energiya samaradorlik qiymatini tasvirlaydi.

6-rasmda magnitlangan qora o'radan ergosohaga tushadigan modda yordamida ajralgan energiya samaradorligini tasvirlaymiz. Chap panel qora o'ra zaryadi Q va magnit maydon B parametrining birgalikdagi ta'sirining energiya samaradorligiga ta'sirini ko'rsatadi, o'ng panel esa ergosferaga tushayotgan massiv zarrachaning qochib ketayotgan qismiga tegishli bo'lgan zaryadlangan zarracha holatida o'zgarmas $Q=0.5$ uchun energiya samaradorligini tasvirlaydi. 6-rasmda (chap panelda) ko'rsatilganidek, energiya samaradorligi η shakli Q ortib borishi bilan yuqoriga siljiydi. Biroq, magnit maydon parametri oshishi bilan u biroz kamayadi. Buning sababi, energiya ajralishi uchun zarur bo'lgan egrosfera sohasi $B > B_{cr}$ qiymatlari uchun kichikroq bo'lib bo'lishi bilan bog'liq. Shuni ta'kidlash kerakki, energiya samaradorlikning maksimal qiymati 50% dan kattaroq qiymatga yetadi, bu esa Kerr qora o'rasi uchun yetarlicha taqqoslanadigan qiymatdir. Bu esa aksial simmetrik magnitlangan Reissner-Nordström qora o'rasining o'ziga xos xususiyatidir. Bundan tashqari, o'ng panelda energiya samaradorligi zaryadlangan zarrachalar holatida 100 % dan ham oshishi mumkinligi ko'rsatildi.

XULOSA

“Gravitatsion relyativistik nazariyalarida kompakt astrofizik ob'ektlarning evolyutsiyasi va dinamikasi” mavzusidagi doktorlik dissertasiya ishining natijalaridan kelib chiqqan holda quyidagi asosiy natija va xulosalar keltiriladi:

1. Yuqori o'lchamlarda qora o'ra hosil bo'lish jarayonlari o'rganildi va Eynshteynning gravitatsiya nazariyasida akkretsion diskda chegaraviy va ichki barqaror aylana orbitalar mavjud bo'lmasligi va shuning uchun yuqori o'lchamlarda ($D > 4$) aylanuvchi qora o'ra hosil bo'lishi mumkin emasligi ko'rsatildi.

2. Yuqori o'lchamli aylanadigan sof Gauss-Bonnet (GB) qora o'ralari atrofida aylana orbitalar o'rganildi va paydo bo'lishi mumkin bo'lgan yagona aylana orbitalarning barchasi beqaror ekanligi va ularning radiusi qo'yi chegaradan foton aylana orbitasi bilan chegaralanganligi ko'rsatildi. Shuningdek, yuqori o'lchamlarda $2N + 2 \leq D \leq 4N$, sof GB/Lovelock aylanadigan qora o'ralar uchun chegaraviy va barqaror aylana orbitalar mavjud bo'lishligi topildi. Eynshteyn gravitatsiyasida yuqori o'lchamli aylanadigan qora o'ralar gravitatsion kollaps /akkretsiya natijasida hosil bo'lishi mumkin emasligi va ular faqat sof GB/Lovelock gravitatsiyasida hosil bo'lishi mumkin degan xulosaga kelindi.

3. Aylanadigan qora o'ralar uchun yuqori o'lchamlarda ovirspin jarayonini o'rganish orqali, kosmik senzura hodisasini tekshirish uchun umumiy formalizm ishlab chiqildi va kosmik senzura hodisasi $D > 5$ o'lchamlarda hatto chiziqli akkretsiya jarayoni uchun ham har doim mavjud bo'lishi ko'rsatildi.

4. Ekstremal va ekstremalga yaqin (2+1) o'lchamli BTZ qora o'ralari uchun Eynshteyn va Eynshteyn-Gaus-Bonnet gravitatsiya nazariyalarida ovicharj jarayoni bajarilishi mumkinligi ko'rsatildi, bu esa kosmik senzura hodisasini (2+1) o'lchamda buzulishiga olib kelishi topildi.

5. Ideal qorong'u moddaning zarralar harakati dinamikasiga, qora o'ralardan energiya ajralishi samaradorligiga, shuningdek qora o'ra dinamikasiga ta'sirini o'rganish orqali formalizm ishlab chiqildi. Qorong'u modda va magnit maydonning o'zaro ta'siri qora o'ra aylanish parametrini $a/M \approx 0.8$ qiymatiga qadar taqlid qilishi mumkinligi ko'rsatildi va ishlab chiqilgan modelga asoslanib ideal qorong'u moddaning yuqori va quyi diapazonlari Sgr A* uchun $\lambda \sim (10^{-21} - 10^{-20})$ va M87 uchun esa $\lambda \sim (10^{-12} - 10^{-11})$ tartibida bo'lishligi topildi.

6. Ideal qorong'u modda va kosmologik doimiyning birgalikdagi ta'sirini o'rganish orqali formalizm taqdim etildi. RN-dS qora o'rasi uchun kosmologik doimiyning itarishish effekti qorong'u moddaning tortishish ta'siridan ustunlik qilishi mumkin bo'lgan ma'lum bir chegara qiymatini analitik ifodasi topildi va bu chegara qiymatidan keyin uning gorizontini buzilishiga olib keladigan ovicharj jarayoni bajarilmasligi ko'rsatildi, shu sababli kosmik senzura hodisasi har dom o'rinli bo'lishi aniqlandi.

7. Aksial simmetrik magnitlangan qora o'rasi fazo-vaqtining geometriyasi va o'ziga xos xususiyatlari o'rganildi va Penrouz jarayoni orqali neytral va zaryadli zarralar uchun aksial simmetrik magnitlangan qora o'rasining magnit maydonini energiya ajralish samaradorligiga ta'siri ko'rsatildi. Shuningdek, magnitlangan Reissner-Nordström qora o'rasi ham huddi Kerr qora o'rasi kabi katta energiya manbai bo'la olishi ko'rsatildi. Bundan tashqari, hatto neytral zarra uchun ham aksial simmetrik magnitlangan ekstremal Reissner-Nordström qora o'rasi ($Q = M$) holati uchun Penrouz jarayoni orqali olingan energiyaning samarador qiymati ekstremal Kerr ($a = M$) qora o'ra uchun topilgan qiymatidan ($\approx 20\%$) deyarli ikki baravar ($\approx 50\%$) kattaligi topildi.

**SCIENTIFIC COUNCIL DSc.03/31.03.2022.T/FM.10.04 ON AWARD OF
SCIENTIFIC DEGREE AT INSTITUTE OF FUNDAMENTAL AND
APPLIED RESEARCH “TIAME” NATIONAL RESEARCH UNIVERSITY**

INSTITUTE OF FUNDAMENTAL AND APPLIED RESEARCH

SHAYMATOV SANJAR RUZIMURATOVICH

**EVOLUION AND DYNAMICS OF COMPACT ASTROPHYSICAL
OBJECTS IN RELATIVISTIC THEORIES OF GRAVITY**

01.04.02- Theoretical physics

**DISSERTATION ABSTRACT OF THE DOCTOR OF SCIENCE (DSc)
ON PHYSICAL AND MATHEMATICAL SCIENCES**

Tashkent – 2022

The theme of the dissertation of doctor of physical and mathematical sciences (DSc) was registered by the Supreme Attestation Commission of the Cabinet of Ministers of the Republic of Uzbekistan under No. B2022.3.DSc/FM196.

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The doctoral (DSc) dissertation can be looked through at the Information Resource Center of the Institute of Fundamental and Applied Research under the National Research University "TIAME" (registered under No.______). Address: Institute of Fundamental and Applied Research, Hall 108, Qori Niyazov Street 39, Tashkent city 100000; Ph.: (+99871) 237-09-61.

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INTRODUCTION (Annotation of doctoral (DSc) dissertation)

Topicality and demand of the theme of dissertation. Through modern astronomical observations the detection of gravitational waves from coalescence of black holes in close binary systems and observation of super-massive black hole M87 and Sgr A* shadow, it has become quite easy to understand the nature of the spacetime geometry and the phenomenon of gravitational interaction in the strong field regime. Those recent observations have provided strong evidence in favor of the existence of black holes in nature and have been expected to be very potent tests in probing unknown aspects associated with precise measurements of the parameters of black holes. In spite of this fact, those current direct and indirect astronomical observations has not shed light on the nature and formation of black holes in higher dimensions, i.e. $D > 4$. The question then arises, what happens and how do rotating black holes form in higher dimensions? Also, Einstein theory of gravity is restricted e.g. due to its non-applicability for the physical singularity appeared, which has remained one of the most important unresolved questions as the limit of GR where it loses its applicability. This all, in turn, leads to require new models and alternative theories of gravity in addressing the above mentioned unanswered questions in general relativity.

During the recent years, our Republic devotes great attention in developing experimental and fundamental researches in the field of relativistic astrophysics. Observational and theoretical investigations have been supported in developing science in all directions in our country. Those studies play significant role in the field of relativistic astrophysics and are reflected in the Strategy of Actions on Further Development of the Republic of Uzbekistan for 2017-2021. As a result, one can point out that theoretical and relativistic astrophysics of gravitational compact objects has been developed by delivering scientific researches at the high and international level in the Republic, i.e., the optical and energetic properties of astrophysical black holes, naked singularities and testing black hole solutions by dynamics of particles in various situations in probing new effects of the general theory of relativity. It is worth noting that, as a consequence of the development of relativistic astrophysics in the republic, there have been arising new directions in the country since scientists pose serious challenges in developing of the qualitative aspects of the nature of compact gravitational objects.

This dissertation work corresponds to the tasks approved in state regulatory documents and in the Decree of the President of the Republic of Uzbekistan No. PD-4947 "On the strategy of Actions on Further Development of the Republic of Uzbekistan" from February 7 and in the "Road-map of the main directions of structural reforms in Uzbekistan for 2019-2021" from November 29, 2018, and others.

Relevance of the research to the priority areas of science and technology development of the Republic of Uzbekistan. The dissertation work has been carried out in accordance with the priority areas of science and technology in the Republic of Uzbekistan: II. "Power, energy and resource saving".

Review of international scientific researches on dissertation subject. The research of black hole formation and dynamics and testing the black hole horizon stability by plunging in matter fields and particles in the strong field regime in various gravity models, investigations of modeling dark matter field on the dynamics of black holes, and studies of energetic properties of black holes are carried out by various leading research centers and institutions, i.e., Max Planck Institute for Gravitational Physics (Germany), University of Frankfurt (Germany), Inter University Center for Astronomy and Astrophysics (India), the California Institute of Technology (CalTech, USA), University of Chicago (USA), Eastern Mediterranean University (Turkey), Institute of Theoretical Physics (China), Division of Physics and Semiconductor Science (Republic of Korea), Tata Institute for Fundamental Research (India), Silesian University in Opava (Czech Republic), Nazarbayev University (Kazakhstan), Fudan University (China), Ulugh Beg Astronomical Institute, (Uzbekistan), Institute of Fundamental and Applied Research (Uzbekistan), and others.

In the black hole evolution, there exist the two main processes are collapse of a matter cloud under its own gravity and accretion of matter onto an already existing gravitating centre. The necessary condition for both the processes to operate is that overall force on collapsing fluid element or on test accreting particles must be attractive. It turns out that this is the case in the usual four dimension for collapsing or accreting matter having nonzero angular momentum. The question then arises, what happens in higher dimensions greater than usual four. From this point of view, it does play increasingly important role to understand more deeply the novel and qualitative aspects of black holes, that is whether both gravitational collapse and accretion can work for formation of rotating black holes in higher dimensions. One can then predict that if and only if both these processes do not operate in higher dimensions to form a rotating black hole and then its effect can be also reflected in the fact that the weak cosmic censorship conjecture is always obeyed even under linear accretion process in $D > 5$. For this situation the pure Lovelock gravity may take center stage and give us a chance to test whether both these above mentioned processes could work for formation of black holes or not in higher dimensions.

Degree of study of the problem. As for the degree of study of the problem many scientists from various research centers and institutions, i.e., Indian scientists (N. Dadhich, P. Joshi, A. Mishra, S. Sarkar, M. Patil, R. Ghosh, etc.), Japan scientists (I. Takahisa, H. Tomohiro, K. Masashi), Italian scientists (C. Bambi, L. Modesto, D. Malafarina, O. Zanotti), Czech scientists (Z. Stuchlik, M. Kolos, J. Schee, J. Kovar, V. Karas), German scientists (C. Laemmerzahl, L. Rezzolla, J. Kuntz, E. Hackmann, D. Kunst, V. Perlick), Chinese scientists (B. Chen, J. Jiang, B. Ge), scientists of republic of Korean (B. Gwak) and others have implemented theoretical and observational investigations for black hole formation and black hole horizon stability by testing WCCC in various theories of gravity. However, those problems have not been thoroughly investigated yet for black holes in higher dimensions $D > 4$ in both Einstein and the pure Lovelock theories of gravity.

The recent investigations and observations show that there is the relevance of the charged particle motion with particle outflows coming out from AGN. In this regard, an extensive analysis has since been developed in a large variety of situations by many scientists, i.e, Indian (M. Wagh, S. Dhurandhar, N. Dadhich), Czech (Z. Stuchlik, M. Kolos, etc.), Ukraine (O. Zaslavskii), Italian (D. Malafarina, E. Barausse), Uzbek (B. Ahmedov and others), Canadian (V. Frolov and others) and by many others addressing the effect of the magnetic field on the energy extraction mechanisms from black holes and accretion disks. However, none of these studies have considered a magnetized black hole solution that causes axially symmetric spacetime due to the existence of magnetic field even without any rotation.

Connection of dissertational research with the plans of scientific research works of the scientific research institution, where the dissertation was conducted. The dissertation work for the period 2021-2022 was carried out within the framework of scientific projects of the Institute of Fundamental and Applied Research and Ulugh Beg Astronomical Institute of Uzbek Academy of Sciences, of the Republic of Uzbekistan F-FA-2021-432 "Analysis and processing of data obtained from satellites for low-mass X-ray binaries" (2021–2026).

The aim of the research dissertation is to develop theoretical formalism that leads to a detailed description of the formation of black hole and its effect to black hole horizon stability in higher dimensions $D > 4$, the effect of perfect fluid dark matter on dynamics of particles and black holes in various situations, the qualitative aspects of the nature of magnetized Reissner-Nordström black hole being a big energy reservoir because of extension of the ergo region and as well as the astrophysical application of the results obtained to the dark matter distributions that exist at the center of galaxies, to the constraint of the validity of alternative models to black holes and to description of high energies from AGN in explaining astrophysical observations.

The tasks of the research:

to study the formation of rotating black holes in higher dimensions by accretion processes in which matter revolves around the gravitating centre in stable circular orbits;

to study stable circular orbits (SCOs) of particles around black holes in higher dimensions in Einstein and pure Lovelock gravity; to develop a general formalism for testing cosmic censorship conjecture by studying the process of over-spinning/overcharging a rotating black hole in higher dimensions $D > 4$ and dimension $D < 4$ for both linear and non-linear particle accretion regime;

to study the influence of perfect fluid dark matter on dynamics of particle motion around black holes in various theories of gravity;

to estimate the value of perfect fluid dark matter by applying its distribution in the center of galaxies of the Sgr A and M87;

the study of the geometry of the axially symmetric magnetized black hole spacetime and the description of efficiency of the energy through the Penrose process for both neutral and charged particles.

The objects of the research are the processes of evolution of black holes in higher dimensions, perfect fluid dark matter, electromagnetic and gravitational fields in the environment surrounding astrophysical black holes in various theories of gravity.

The subjects of the research are black hole formation, its dynamics as well as testing black hole horizon stability in higher dimensions, the influence of perfect fluid dark matter on astrophysical process associated with observational data, and the energy efficiency in axially symmetric magnetized black hole spacetime as well.

The methods of the research. In the dissertation, we use the mathematical apparatus of general relativity and metric affine differential geometry, analytical and numerical methods for solving differential equations of particle dynamics and fields.

The scientific novelty of the research is the follows:

for the first time, the processes of black hole formation has been studied in higher dimensions; It is shown that, for Einstein gravity, stable circular orbits cannot exist for accretion disk to form, and hence a rotating black hole cannot be formed in higher dimensions $D > 4$;

for the first time a general formalism for testing cosmic censorship conjecture by studying the process of overspinning a rotating black hole in higher dimensions has been developed; it has been shown that the weak cosmic censorship conjecture is always obeyed even under linear accretion process in $D > 5$;

for the first time it has been shown that extremal and near-extremal (2+1) dimensional BTZ black holes can be overcharged in both Einstein and Einstein-Gauss-Bonnet theories of gravity, thus resulting in not obeying weak cosmic censorship conjecture;

for the first time we develop a formalism by studying the influence of perfect fluid dark matter on dynamics of particle motion, energy efficiency extracted from black holes as well as black hole dynamics; it has been shown that, from an observational point of view, it would not be possible for far away observers to distinguish between a Kerr black hole in vacuum from a black hole with large angular momentum and immersed in a dark matter envelope with external magnetic field;

for the first time we present a formalism by studying the combined effects of perfect fluid dark matter and cosmological constant together; it has been shown that the RN-dS black hole cannot always be overcharged beyond a certain threshold limit for which a repulsive effect arising from the cosmological constant dominates over the attractive one due to the perfect fluid dark matter;

for the first time the study of the geometry, the novel and qualitative aspects of the axially symmetric magnetized black hole spacetime and the effect of its magnetic field on the efficiency of the energy through the Penrose process for both neutral and charged particles are presented; it has been shown that the magnetized

Reissner-Nordström black hole would be a big energy reservoir as a Kerr black hole with angular momentum.

Practical results of the research are as follows:

It has been proven that there cannot exist stable circular orbits to form accretion disk in higher dimensions in Einstein gravity, and thus a rotating black hole cannot be formed in $D > 4$;

it has been shown that the occurrence of no stable circular orbits can be reflected in the fact that rotating black holes can not be overspun even under linear accretion process in $D > 5$;

it has been shown that the combined effects of dark matter and magnetic field can mimic the black hole rotation parameter up to $a/M \approx 0.8$; following the developed model the upper and lower ranges of perfect fluid dark matter have been estimated, i.e., it would be of the order $\lambda \sim (10^{-21} - 10^{-20})$ for the Sgr A * and $\lambda \sim (10^{-12} - 10^{-11})$ for the galaxy M87;

the analytical expressions for a certain threshold limit for which a repulsive effect due to the cosmological constant dominates over the attractive effect of the perfect fluid dark matter has been obtained; it has been demonstrated that beyond this threshold limit the RN-dS black hole cannot be overcharged and hence the weak cosmic censorship conjecture is strongly respected;

it has interestingly been observed that even for the case of neutral particle the efficiency of the Penrose process for the extremal ($Q = M$) case of the axially symmetric magnetized Reissner-Nordström is more than double ($\approx 50\%$) to that of the extremal Kerr ($a = M$) black hole case which is about $\approx 20\%$.

Reliability of the research results is provided by the facts that, in the dissertation work standard methods of general relativity as well as methods of mathematical and theoretical physics were used with modern numerical methods and programs; the obtained theoretical results were compared by having a thorough check with the available theoretical data and modern astronomical observations and the results of other scientists; the given conclusions of results are in good agreement with the general principles of the field theory of compact gravitational objects in the strong gravity regime.

Scientific and practical significance of the research results. The scientific significance of the research results in the dissertation consists in developing formalisms to analyze the formation of rotating black holes and to test cosmic censorship conjecture by studying the process of overspinning rotating black holes with particle accretion for obtaining general information and strong mathematical proof in order to understand more deeply the novel and qualitative aspects of black holes in higher dimensions $D > 4$. In addition, energetic particles are produced by collisions in the accretion disk and the disk's luminosity depends on the underlying geometry. However, in a realistic scenario the object cannot be considered to be in vacuum, as we know that dark matter distributions exist at the center of galaxies. Also magnetic fields play an important role in the dynamics of charged particles

around black holes, especially close to the black hole's horizon. Therefore, in order to have confidence in the conclusions drawn from the observations of accretion disks, it is important to study the effects that the presence of external matter fields and magnetic fields have on the particles in the disks.

The practical significance of the results of the dissertation consists in facts that, from an observational point of view, the obtained results suggest that the determination of the ISCO from the observation of electromagnetic radiation emitted by the accretion disk could not suffice to establish the value of the source's angular momentum. In fact, it would not be possible for far away observers to distinguish between a Kerr black hole in vacuum from a black hole with smaller angular momentum and immersed in a dark matter field and from a magnetized black hole with larger angular momentum. Thus, these theoretical studies in the dissertation can help constraint the validity of alternative models to black holes in explaining astrophysical observations. Also, theoretical analysis of the upper and lower range of the perfect fluid dark matter's distribution around the supermassive black holes can be used to analyze the nature and dynamics of the dark matter field in developing observational data through signals that come far away from gravitational objects by interacting with intermediate matters. The obtained results regarding energy efficiency extracted from axially symmetric magnetized black hole spacetime can be useful in the analysis of astronomical observations associated with the outflows having large energies from active galactic nuclei in the form of winds and jets. The results associated with analyses of remarkable aspects of black holes in higher dimensions can be used as an accepted model to developing further methods and explaining the evolution of rotating black holes in higher dimensions in the universe.

Implementation of the research results. Based on investigations of evolution and dynamics of compact astrophysical objects in relativistic theories of gravity:

the theoretical research results and methods on the circular orbits around higher dimensional Einstein and pure Gauss-Bonnet rotating black holes and black hole formation have been used in the frame of the Inter-University Centre for Astronomy and Astrophysics programs supported by the University Grants Commission (letter from the Inter-University Centre for Astronomy and Astrophysics, Inida, dated November 25, 2022), and by a number of foreign authors (Physics of the Dark Universe, Vol. 35, id. 100916, 2022; Physical Review D, Vol. 105, id. 124033, 2022; Classical and Quantum Gravity, Vol. 38, id. 155017, 2021) to examine photon motion and its shadow around rotating charged black hole in 4D EGB gravity and stable bound orbits around static Einstein-Gauss-Bonnet black holes and etc. using the analytical and numerical calculations;

the scientific results on overspinning and overcharging of black holes in higher ($D > 4$) and lower ($2+1$) dimensions have been used by several foreign scientists (Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 077, 2022; Physical Review Research, Vol. 4, id. 023031, 2022; The European Physical Journal C, Vol. 81, id. 1131, 2021; Physics of the Dark Universe, Vol. 32, id.

100831, 2021; Journal of High Energy Physics, Vol. 2021, id. 45, 2021; The European Physical Journal C, Vol. 81, id. 49, 2021) in developing different models associated with stability of horizon in various gravity models. Application of results obtained in the dissertation would allow to develop fundamental theories of testing the stability of a black hole horizon in other gravity models;

the research results on effect of perfect fluid dark matter on particle motion around a static black hole immersed in an external magnetic field and the combined effects of perfect fluid dark matter and cosmological constant together have been used by several foreign researchers (Physics Letters B, Vol. 829, id. 137031, 2022; Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 077, 2022; Journal of Cosmology and Astroparticle Physics, Vol. 2021, id. 012, 2021; Physical Review D, Vol. 104, id. 084015, 2021; Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 043, 2022; Universe, Vol. 8, id. 369, 2022; Physical Review D, Vol. 103, id. 104070, 2021; Communications in Theoretical Physics, Vol. 73, id. 095403, 2021; The European Physical Journal C, Vol. 81, id. 269, 2021) to develop the formalism of regular nonminimal magnetic black hole as a source of quasiperiodic oscillations, of exploring millicharged dark matter components from the shadows, and of Joule-Thomson expansion of RN-AdS black hole immersed in perfect fluid dark matter in various gravity models;

the results devoted to reveal the qualitative aspects of axially symmetric magnetized black hole spacetime geometry and its magnetic field to bring out its effect on the astrophysical phenomena and the extracted energy efficiency have been used in the frame of Institute of Physics and Mathematics, Michoacana University Research Grant No. CF-MG-2558591 FORDECYT-PRONACES CONACYT (letter from Institute of Physics and Mathematics, Michoacana University in San Nicolás de Hidalgo, Mexico), as well as by a number of foreign researchers (Physical Review D, Vol. 105, id. 064072, 2022; International Journal of Modern Physics A, Vol. 37, id. 2250144, 2022; The European Physical Journal Plus, Vol. 137, id. 645, 2022; Universe, Vol. 8, id. 571, 2022; The European Physical Journal Plus, Vol. 136, id. 1032, 2021; The European Physical Journal C, Vol. 81, id. 983, 2021; Physical Review D, Vol. 104, id. 064016, 2021; Galaxies, Vol. 9, issue 4, id. 71, 2021; Galaxies, Vol. 9, id. 63, 2021) to develop the theoretical study of dynamics of charged particles in the field of quantum-corrected static black holes and of gravitational analog of Faraday rotation in the magnetized Kerr and RN spacetimes, and etc.

Approbation of the research results. The research results were reported and discussed at 3 international and local scientific conferences.

Publication of the research results. On the dissertation theme there were published 23 scientific works, of them 20 scientific papers, including 19 international ones, were published in scientific referred journals recommended by the Supreme Attestation Commission of the Republic of Uzbekistan for publishing basic scientific results of doctoral theses.

Volume and structure of the dissertation. The dissertation consists of an introduction, four chapters, conclusion and a bibliography. The size of the dissertation is 218 pages.

THE MAIN CONTENTS OF THE DISSERTATION

In the introduction the topicality and demand of the dissertation theme, the main aims set out on the dissertation and the scientific novelty and the practical results were underlined, the reliability of the results and their theoretical and practical significance were emphasized, and the application of the research results and the dissertation structure were satated.

The first chapter of the dissertation entitled “Black hole formation and dynamics in higher dimensions” is devoted to demonstrate the processes of black hole formation by considering accretion of matter onto an already existing gravitating centre and to show whether the bound orbits/ISCOs do exist around rotating black holes in higher dimesntions.

There is the well known Myers-Perry solution describing a rotating black hole in higher dimensions. The line element for that is given by

$$ds^2 = -dt^2 + r^2 d\beta^2 + \sum_{i=1}^n (r^2 + a_i^2)(d\mu_i^2 + \mu_i^2 d\phi_i^2) + \frac{\mu r}{\Pi F} (dt + \sum_{i=1}^n a_i \mu_i^2 d\phi_i)^2 + \frac{\Pi F}{\Delta} dr^2, \quad (1)$$

with

$$F = 1 - \sum_{i=1}^n \frac{a_i^2 \mu_i^2}{r^2 + a_i^2}, \quad \Pi = \prod_{i=1}^n (r^2 + a_i^2), \quad \Delta = \Pi - 2\mu r^{2n-D+3}. \quad (2)$$

Here μ and a_i are black hole mass and rotation parameters, and μ_i and β are related by the following expressions,

$$\sum_{i=1}^n \mu_i^2 + \beta^2 = 1, \quad \text{and} \quad \sum_{i=1}^n \mu_i^2 = 1, \quad (3)$$

for $D = 2n + 2, 2n + 1$ respectively, the latter results when $\beta = 0$ is satisfied in the former as well as in the metric. Note that μ_i are the direction cosines, for example, μ_1 and μ_2 for $D = 5, 6$ dimensions will respectively read as

$$\mu_1 = \sin\theta \quad \text{and} \quad \mu_2 = \cos\theta, \quad (4)$$

and

$$\mu_1 = \sin\theta, \quad \mu_2 = \cos\theta \sin\chi \quad \text{and} \quad \beta = \cos\theta \cos\chi. \quad (5)$$

Note that in higher dimensions, black hole can have more than one rotations, and $n = [(D - 1)/2]$ is the maximum number of rotations it can have in the given dimension D ; i.e., $n = 2$ for $D = 5, 6$ dimensions.

In particular we would examine the case of 5 and 6 dimensions and show that (i) effective potential, $V_{eff} > 1$ always for non-zero angular momentum, and (ii) it has only a maximum and no minimum and hence there can occur no bound and stable circular orbits. Following the standard procedure for geodesic motion of timelike particles in the equatorial plane around a rotating black hole, we would write the effective potential. We thus define the effective potential for equatorial

motion of particle in the field of a six dimensional black hole with a single rotation, and it is given by

$$V_{eff}(r) = -\frac{g_{t\phi}}{g_{\phi\phi}} \mathcal{L} + \sqrt{\frac{\Delta}{g_{\phi\phi}} \left(1 + \frac{\mathcal{L}^2}{g_{\phi\phi}}\right)}. \quad (6)$$

Here we have used the specific physical quantities, $\mathcal{E} = E/m$ and $\mathcal{L} = L/m$ and have set $m^2 = 1$. From Eq. (6) we write the effective potential $V_{eff}(r)$ for $D = 5, 6$ dimensions in the following form:

$$V_{eff}^{5D}(r) = \frac{a\mu\mathcal{L}}{r^4 + (r^2 + \mu)a^2} + \frac{r(r^4 + (r^2 + \mu)a^2 + r^2\mathcal{L}^2)^{1/2}}{r^4 + (r^2 + \mu)a^2} \times (r^2 - \mu + a^2)^{1/2}, \quad (7)$$

$$V_{eff}^{6D}(r) = \frac{a\mu\mathcal{L}}{r^5 + (r^3 + \mu)a^2} + \frac{r(r^5 + (r^3 + \mu)a^2 + r^3\mathcal{L}^2)^{1/2}}{r^5 + (r^3 + \mu)a^2} \times (r^3 - \mu + a^2r)^{1/2}. \quad (8)$$

On expanding for large r , these take the form

$$V_{eff}^{5D}(r \rightarrow r_\infty) \sim 1 + \frac{(\mathcal{L}^2 - \mu)}{2r^2} + \mathcal{O}\left(\frac{1}{r^4}\right), \quad (9)$$

$$V_{eff}^{6D}(r \rightarrow r_\infty) \sim 1 + \frac{\mathcal{L}^2}{2r^2} - \frac{\mu}{2r^3} + \mathcal{O}\left(\frac{1}{r^4}\right),$$

which clearly show that the repulsive centrifugal component would override the attractive gravitational one for $D > 4$. Note that when $\mathcal{L} = 0$, effect of black hole rotation dies out sharply leaving only the attractive component.

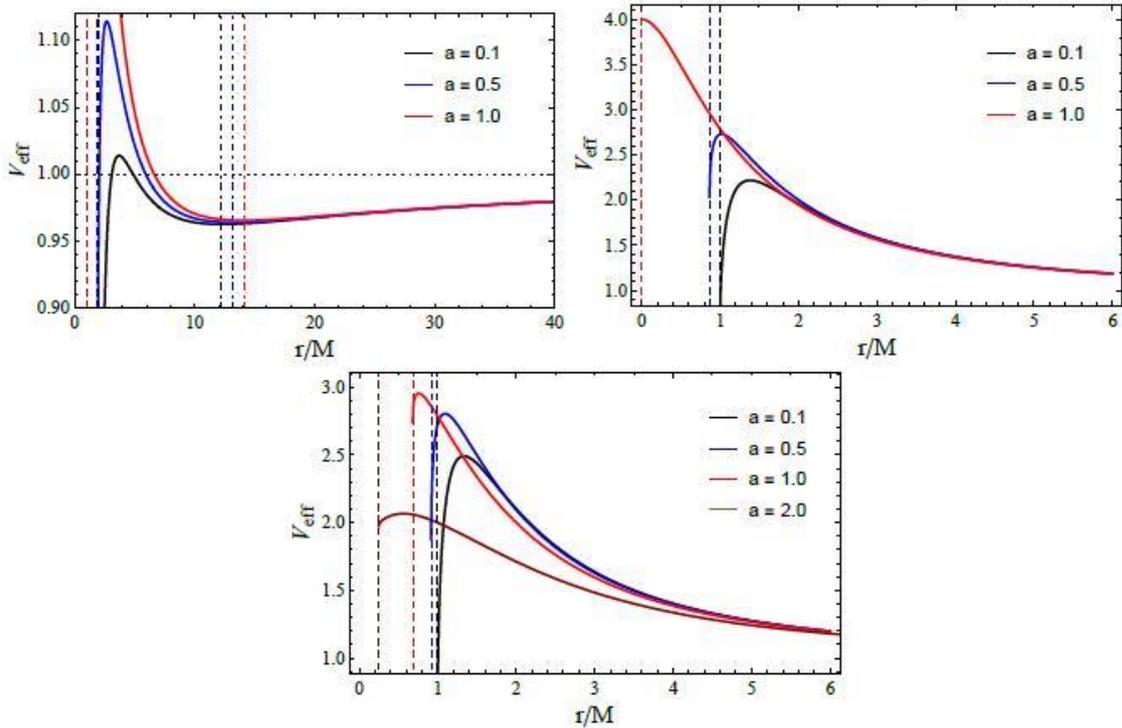


Fig. 1. Effective potential plots for $L = 4$: Left, right and below panels respectively refer to $D = 4, 5, 6$. The vertical dashed lines indicate location of horizon while the vertical dot-dashed lines indicate location of minimum of V_{eff}

As shown in Fig. 1, this clearly shows that $V_{eff} \geq 1$ always for the latter while for the former when $\mathcal{L}^2 > \mu$. For both $D = 5, 6$ $V_{eff} = 1$ at infinity, and then it rises as r decreases and reaches maximum before coming down at horizon. It is interesting that $V_{eff} \geq 1$ all through except very close to horizon. This is in contrast to the four-dimensional case where $V_{eff} \leq 1$ away from horizon. For a single rotation, there occurs only one horizon and hence there is no upper limit on rotation parameter a except for five dsimension where it has to respect $a^2 \leq M$ lest it turns into a naked singularity¹. This is an interesting case of a rotating black hole with one horizon yet having an extremal limit for its rotation parameter. It is also interesting to note that in $D = 6$, as $a \rightarrow \infty$, $V_{eff} \rightarrow 1$ at all r . This is why initially maximum of curve rises with increasing a until $a \sim 1.3$, then it starts coming down. Further it has only one extremum which is a maximum and there is no minimum. This means there can neither occur any bound orbit nor a stable circular orbit. This is the characteristic feature of particle motion for rotating black holes in higher dimensions.

In Fig. 1. above, we have plots of effective potential for $\mathcal{L} = 4$ in $D = 4, 5, 6$. For the zero angular momentum case, the potential for large r goes as $1 - \mu/2r^{D-3}$ and hence it would always be ≤ 1 . That is, asymptotically contribution due to black hole rotation fades out, leaving only the one due to mass. What distinguishes four dimension (upper left panel) from $D > 4$ (upper right and lower panels) is the fact that $V_{eff} \leq 1$ while in contrast it is opposite for the others. As a matter of fact it is greater than unity everywhere except near the horizon in $D > 4$, reaching unity from the above and has only a maximum and no minimum. That means there can exist no potential well to harbour bound and SCOs. Thus it is no surprise that bound orbits and thereby SCOs cannot exist around rotating black holes in higher dimensions. This raises the critical question about accretion process in higher dimensions. Accretion is mediated through accretion disk which cannot occur because there exist no bound orbits and consequently no SCOs. This is true for both rotating as well as non-rotating black holes in higher dimensions. Accretion disk provides avenue for dissipative interactions involving viscosity and collisions between particles through which particles can lose angular momentum and keep on falling inward and spiral into the black hole with $L < L_{ISCO}$. Since stable circular orbits cannot exist in higher dimensions for accretion disk to form, hence an accretion process cannot ensue. It can therefore play no role in formation of a rotating black hole in higher dimensions.

The second chapter of the dissertation entitled “Testing black hole horizon’s stability in dimensions $D < 4$ and higher dimensions $D > 4$ ” is devoted to develop a general formalism for testing cosmic censorship conjecture by studying the process of overspinning/overcharging a rotating black hole in higher dimensions $D > 4$ and dimension $D < 4$ for both linear and non-linear particle accretion regime.

¹ This happens only in the special case of five dimension and not in general for $D = 2n + 1$, because in this case contribution to potential due to both mass and rotation falls as $1/r^2$.

We first test the validity of the weak cosmic censorship conjecture for the $(2 + 1)$ -dimensional charged black hole solutions derived by Martinez, Teitelboim, and Zanelli (MTZ) in Einstein and Einstein-Gauss-Bonnet theories of gravity. For that, We start with the Einstein-Hilbert-Maxwell action:

$$\mathcal{S} = \int d^3x \sqrt{-g} \left(\frac{R-2\Lambda}{16\pi} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right). \quad (10)$$

Here $F_{\mu\nu}$ is tensor of electromagnetic field, while R is the scalar curvature of the spacetime. After solving the field equations in Hamiltonian form with the assumptions of rotational symmetry and time independence, Martinez-Teitelboim-Zanelli (MTZ) obtained the following solution representing a charged black hole without angular momentum

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2, \quad (11)$$

where the metric function

$$f(r) = r^2 - M - \left(\frac{Q}{2}\right)^2 \ln(r^2), \quad (12)$$

with M being MTZ black hole mass and Q being the total electric charge of black hole. The function $f(r)$ has a minimum at $r_{\min} = Q/2$. The value of this function at its minimum is

$$f(r_{\min}) = -M + \left(\frac{Q}{2}\right)^2 \left[1 - \ln\left(\frac{Q}{2}\right)^2\right]. \quad (13)$$

There are three possibilities to characterize the spacetime: If $f(r_{\min}) = f(Q/2) < 0$, there exist two roots of $f(r)$. Then we have a usual black hole with r_+ , and r_- , as the inner and outer horizons. If $f(r_{\min}) = f(Q/2) = 0$, the two roots coincide and we have an extremal black hole. If $f(r_{\min}) = f(Q/2) > 0$, there are no real roots of $f(r)$, hence we have a naked singularity. The case of extremal black holes corresponds to $f(Q/2) = 0$. Since $f(r_+) = 0$ by definition, for an extremal black hole, we have $r_+ = Q/2$. For a black hole solution, we require $f(r_{\min}) \leq 0$, i.e.

$$\delta \equiv M - \left(\frac{Q}{2}\right)^2 \left[1 - \ln\left(\frac{Q}{2}\right)^2\right] \geq 0. \quad (14)$$

Note that the function $(Q/2)^2 [1 - \ln(Q/2)^2]$ vanishes at $Q = 0$ and $(Q/2)^2 = e$, but has a maximum at $(Q/2)^2 = 1$ (or $Q = 2$), which is equal to 1. Thus, if $M > 1$, δ is always larger than zero so we have an ordinary black hole with r_+ and r_- .

We have shown that an extremal and a nearly MTZ black hole could be overcharged. We would like to check the hypothesis whether could a near extremal black hole be overcharged or not if one takes all the second order perturbations into account. Here we follow the work of Sorce and Wald, where the authors argued that the violation of WCCC for nearly extremal black holes can be fixed by considering all non-linear order perturbations. In other words, in this section, we adapt their method to check the overcharging of MTZ black holes by considering all the second order perturbations. Let's now recall Eq. (14),

$$\delta \equiv M - \left(\frac{Q}{2}\right)^2 \left[1 - \ln\left(\frac{Q}{2}\right)^2\right].$$

The cases with $\delta > 0$ represent black hole solutions while the cases with $\delta < 0$ correspond to objects without an event horizon. We have shown that $\delta(\lambda)$ will be negative even one includes the second order terms $\delta^2 E$ and $\delta^2 Q$. Therefore the second order perturbations cannot compensate for the overcharging of nearly extremal MTZ black holes. This allows us to understand the nature of the MTZ black hole better in dimensions $D < 4$ as its horizon is not stable as compared to the one in four dimensions. This is an interesting aspect of the charged MTZ black hole in dimension $D < 4$ that refuses what is true for black holes in four dimension. We also conclude that near extremal $(2 + 1)$ dimensional BTZ black hole in EGB theory can also be overcharged similar to the $(2 + 1)$ dimensional MTZ black hole in Einstein gravity, thus resulting in violating the WCCC. The result would continue to do so for charged test particle perturbations.

We then further test the validity of the WCCC for black holes with $(n - 1)$ and n rotations in higher dimensions $D > 4$. It turns out that black hole with $(n - 1)$ rotations behave characteristically differently from that with maximum allowed $n = [(D - 1)/2]$ rotations in a given dimension D . We shall consider these two cases separately. The line element of the higher dimensional rotating Myers-Perry black hole in odd $D = 2n+1$ and even $D = 2n+2$ dimensions is given by Eq. (1). Black hole horizon is given by $\Delta = 0$ and which in odd and even dimensions will respectively read as follows:

$$(r^2 + a_1^2) \dots (r^2 + a_i^2) - \mu r^2 = 0, \quad (15)$$

and

$$(r^2 + a_1^2) \dots (r^2 + a_i^2) - \mu r = 0. \quad (16)$$

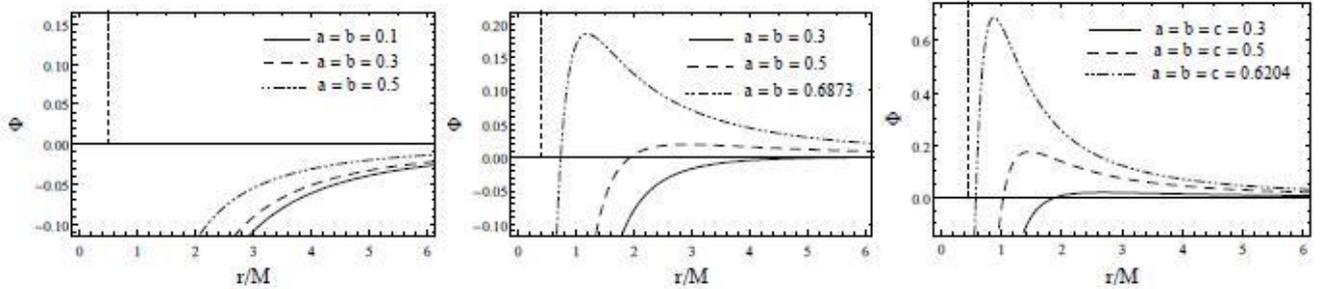


Fig. 2. From left to right: Potential $\Phi(r)$ for $D=5,6,7$ is plotted against r/M . In all panels, vertical dashed line indicates the horizon for near extremal values of rotation parameters for which plot is shown by dot-dashed lines.

Effective gravitational potential for black holes with n rotations is given by,

$$\Phi(r) \approx \frac{\Delta}{r^2} - 1 = \frac{(r^2 + a^2) \dots (r^2 + a_n^2)}{r^{2n}} - \frac{\mu}{r^{D-3}} - 1. \quad (17)$$

Fig. 2 shows plots of $\Phi(r)$ and its derivative from left to right for $D = 5, 6, 7$. This clearly shows that overall acceleration is attractive all through for $D = 5$ while it is repulsive for $D = 6, 7$ for large r/M . This would be the same in all higher dimensions ≥ 6 . It however turns attractive closer to horizon which is because horizon occurs for $r/M < 1$ where attractive component, $1/r^{D-3}$ rides over repulsive $1/r^2$ as well as relative dominance of mass over rotation parameters.

In the dissertation, it has been shown by explicit calculation that six dimensional black hole with two rotations cannot be overspun under linear accretion. As we have seen above that in all higher dimensions > 6 gravitational dynamics would be similar to that in $D = 6$, hence what happens in six dimensions should hold true in all higher dimensions as well. That is, black holes having the maximum number of allowed rotations in all $D \geq 6$ cannot similarly be overspun. We could thus state: *Theorem I*: A black hole in a given dimension having one of its rotations zero (i.e. $(n - 1)$ rotations) can never be overspun and hence would always obey WCCC and *Theorem II*: Black hole in dimension > 5 can never be overspun under linear accretion and would thereby always obey WCCC. If a black hole cannot be overspun under linear accretion, it would continue to do so for non-linear perturbations because the latter always favours no overspinning and thereby the WCCC.

The third chapter of the dissertation entitled “Effect of perfect fluid dark matter on dynamics of particle motion and black holes” is devoted to study the influence of perfect fluid dark matter (PFDM) on dynamics of particles and black holes in various theories of gravity and to estimate its value by applying its distribution in the center of galaxies of the Sgr A and M87.

The metric describing a static and spherically symmetric black hole immersed in perfect fluid dark matter in Schwarzschild coordinates (t, r, θ, φ) is given by

$$ds^2 = -F(r)dt^2 + F(r)^{-1}dr^2 + r^2d\Omega^2, \quad (18)$$

where $d\Omega^2$ is the line element on the unit 2-sphere and where we have defined

$$F(r) = \left(1 - \frac{2M}{r} + \frac{\lambda}{r} \log \frac{r}{|\lambda|}\right), \quad (19)$$

with M being black hole mass and λ related to the dark matter density and pressure. In the case of $\lambda \neq 0$ the stress energy-momentum tensor of the dark matter distribution is that of an anisotropic perfect fluid $T_{\nu}^{\mu} = \text{diag}(-\rho, p_r, p_{\theta}, p_{\phi})$ where density, radial and tangential pressures are given by

$$\rho = -p_r = \frac{\lambda}{8\pi r^3} \quad \text{and} \quad p_{\theta} = p_{\phi} = \frac{\lambda}{16\pi r^3}. \quad (20)$$

In the limit of $\lambda \ll 1$ we can write the approximate expressions for the ISCO radius r_i and the photon orbit r_{ph} as

$$r_i \approx 6M + \left[4 - 3\log\left(\frac{6M}{\lambda}\right)\right] \lambda + O(\lambda^2), \quad (21)$$

$$r_{ph} \approx 3M + \frac{1}{2} \left[1 - \log\left(\frac{27}{8}\right)\right] \lambda + O(\lambda^2). \quad (22)$$

Solving Maxwell equations the covariant components of the 4-potential of the electromagnetic field for the perfect fluid dark matter field have been obtained as

$$A_t = A_r = A_{\theta} = 0, \\ A_{\varphi} = \frac{B}{2} r^2 \left[1 + \frac{\lambda}{r} \left(1 + \log \frac{M}{r}\right) + O(\lambda^2)\right] \sin^2 \theta.$$

For the charged test particle the effective potential which determines the motion of the particle is given by

$$V_{eff} = F(r) \left(1 + \frac{[\mathcal{L} - \frac{b}{M} (1 + \frac{\lambda}{r} (1 + \log \frac{M}{r})) r^2]^2}{r^2} \right), \quad (23)$$

and where we have used the specific constants of motion per unit mass, namely $\mathcal{E} = E/m$, $\mathcal{L} = L/m$. The magnetic parameter $b = qBMG/mc^4$ measuring the effect of the magnetic field on the charged particle motion.

In Fig. 3 we show the radial dependence of V_{eff} for different values of λ and b . We see that the presence of dark matter, i.e. $\lambda > 0$ has the opposite effect with respect to the magnetic field when $b > 0$, in terms of the strength of the potential, therefore suggesting the possibility that these two effects may cancel each other at some radius for certain values of λ and b . On the other hand we notice that regardless of the sign of the magnetic field parameter, the ISCO radius is always smaller with respect to the Schwarzschild case, thus suggesting that the geometry could be distinguished from the Schwarzschild geometry, provided that one is able to have an independent measurement of M . Notice that the values of b and λ in the first row of Fig. 3 are purely illustrative. Regarding b the upper limit discussed at the beginning of this section may be greatly reduced when the test particles are atoms or molecules, which may have the same charge but much larger mass than elementary particles such as electrons. The effective potential for more realistic values of b is illustrated in the second row of Fig. 3.

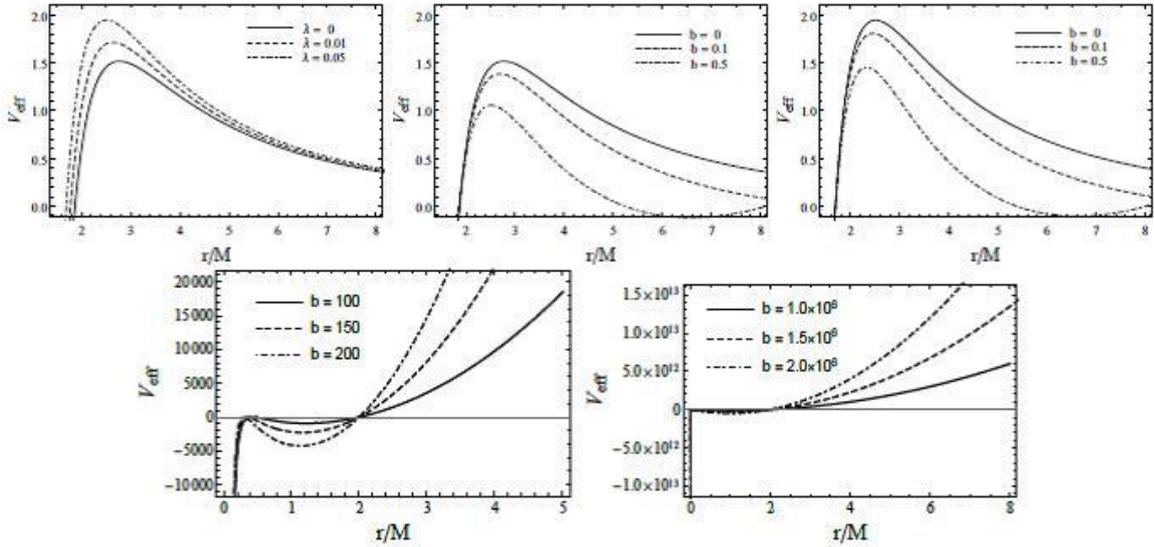


Fig. 3. Radial dependence of the effective potential for massive particles around a black hole in perfect fluid dark matter immersed in an external asymptotically uniform magnetic field. Top row, left panel: V_{eff} is plotted for different values of λ in the case without magnetic field, i.e. $b=0$. Top row, middle panel: V_{eff} is plotted for different values of b in the case without dark matter, i.e. $\lambda=0$. Top row, right panel: V_{eff} is plotted for different values of b in the case of fixed $\lambda=0.05$. The two panels in the bottom row show how V_{eff} is affected by considering more realistic values of $b \gg 1$ while keeping fixed $\lambda=0.05$.

From an observational point of view, far away observers would not be able to distinguish between the two geometries by analyzing electromagnetic radiations emitted by gas on the accretion disk orbiting around the central object. Notice that the combined effects of dark matter and magnetic field can mimic the black hole rotation parameter up to $a/M \approx 0.75 - 0.8$, whereas dark matter alone can mimic only up to $a/M \approx 0.35$; Fig. 4. This suggests that a measurement of the angular momentum of a black hole candidate may be affected up to 30% by the presence of dark matter in its surroundings and even more if external magnetic fields are present.

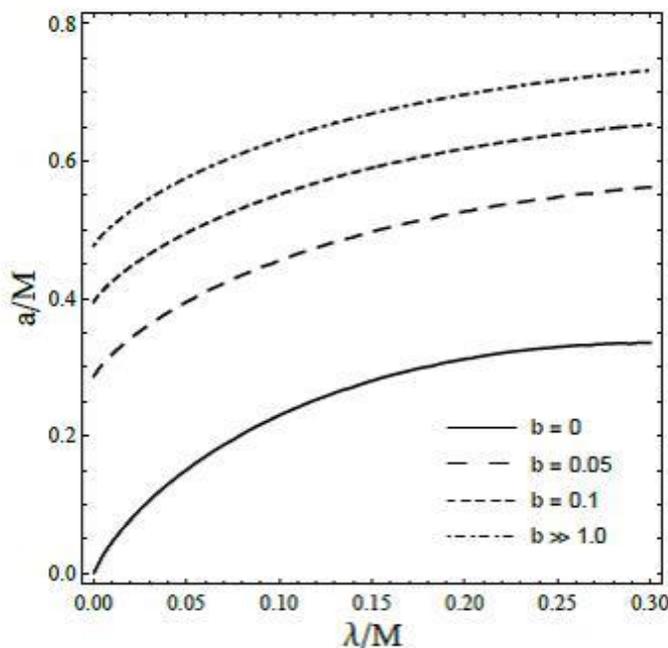


Fig. 4. The degeneracy for the location of the ISCO between the Kerr case and the perfect fluid dark matter case. The plot shows the values of a as a function of λ for which the radius of the ISCO in the Kerr geometry is the same as the ISCO in the perfect fluid dark matter geometry. The degeneracy is illustrated for different values of b , showing that increase in the external magnetic field allows to mimic higher values of the angular momentum for a given value of λ .

When applied to astrophysical black holes, the above qualitative argument, suggests that the measurement of highly spinning black hole candidates may be also regarded as due to black holes with lower spin immersed in a dark matter envelope. Regarding λ , since we do not know the characteristic dark matter densities at the center of galaxies (namely within a few Schwarzschild radii from the central object) we can not estimate a realistic value. However we can be somewhat more quantitatively considering dark matter estimates within few parsecs from the central object. There are several studies that discuss the well-known disagreement between the results that stems from numerical simulations and observations of low-mass galaxies, known as the core-cusp problem, according to which dark matter densities as inferred from observations lie between $\rho \sim$

$(10^{-2} - 10^{-1})M_{\odot}/pc^3$. Following this estimate we may obtain the corresponding value of λ as per the model considered here. For example: the dark matter parameter would be of the order $\lambda \sim (10^{-21} - 10^{-20})$ for the Sgr A* and $\lambda \sim (10^{-12} - 10^{-11})$ for the galaxy M87.

The fourth chapter of the dissertation entitled “Efficiency of Penrose process in spacetime of axially symmetric magnetized Reissner-Nordström black hole” is devoted to study the geometry and the novel and qualitative aspects of the axially symmetric magnetized black hole spacetime and the description of efficiency of the energy through the Penrose process for both neutral and charged particles.

The spacetime metric describing axially symmetric magnetized Reissner-Nordström black hole in Schwarzschild coordinates (t, r, θ, ϕ) is given by

$$ds^2 = H (-Fdt^2 + F^{-1} dr^2 + r^2 d\theta^2) + H^{-1} r^2 \sin^2 \theta \times (d\phi - \omega dt)^2, \quad (24)$$

where

$$F = 1 - \frac{2M}{r} + \frac{Q^2}{r^2}, \quad (25)$$

$$H = 1 + \frac{1}{2} B^2 (r^2 \sin^2 \theta + 3Q^2 \cos^2 \theta) + \frac{1}{16} B^4 (r^2 \sin^2 \theta + Q^2 \cos^2 \theta)^2, \quad (26)$$

$$\omega = -\frac{2QB}{r} + \frac{1}{2} QB^3 r (1 + F \cos^2 \theta), \quad (27)$$

with parameters M and Q correspond to the black hole mass and charge. Note that B refers to the magnetic field parameter. The above metric reduces to the Reissner-Nordström black hole one in the limit of $B \rightarrow 0$, while the Schwarzschild one in the limit of $B, Q \rightarrow 0$. It is worth noting that, interestingly, it turns out that the magnetized black hole also causes axially symmetric spacetime due to the existence of magnetic field without any rotation. It is a remarkable property of magnetized Reissner-Nordström black hole.

As can be seen from Fig. 5, the ergo region can extend to infinity far away from black hole in both negative and positive z directions. The point to be noted is that the ergoregion is separated from black hole for small values of magnetic parameter B , while it merges with the black hole for its large values as seen in *right panel* of fig:ergo. It then results in increasing the appropriate volume of ergoregion for larger values of parameter B , thereby leading to arbitrarily high energy efficiency in the Penrose process. This is a remarkable nature of the magnetized black hole spacetime in contrast to other axially symmetric black holes. It is worth noting here that in Fig. 6, we consider only the extremal case (i.e. $Q = 1$ and $M = 1$) of the axially symmetric magnetised black hole and bring out the effect of magnetic field on the ergoregion. The main motivation to show the ergoregion for the extremal case in Fig. 5 is coming from the well established fact in the literature that the energy extracted via Penrose process from the rotating black hole is maximum only when the black hole satisfying the extremal condition (i.e. cauchy and event horizons coincide).

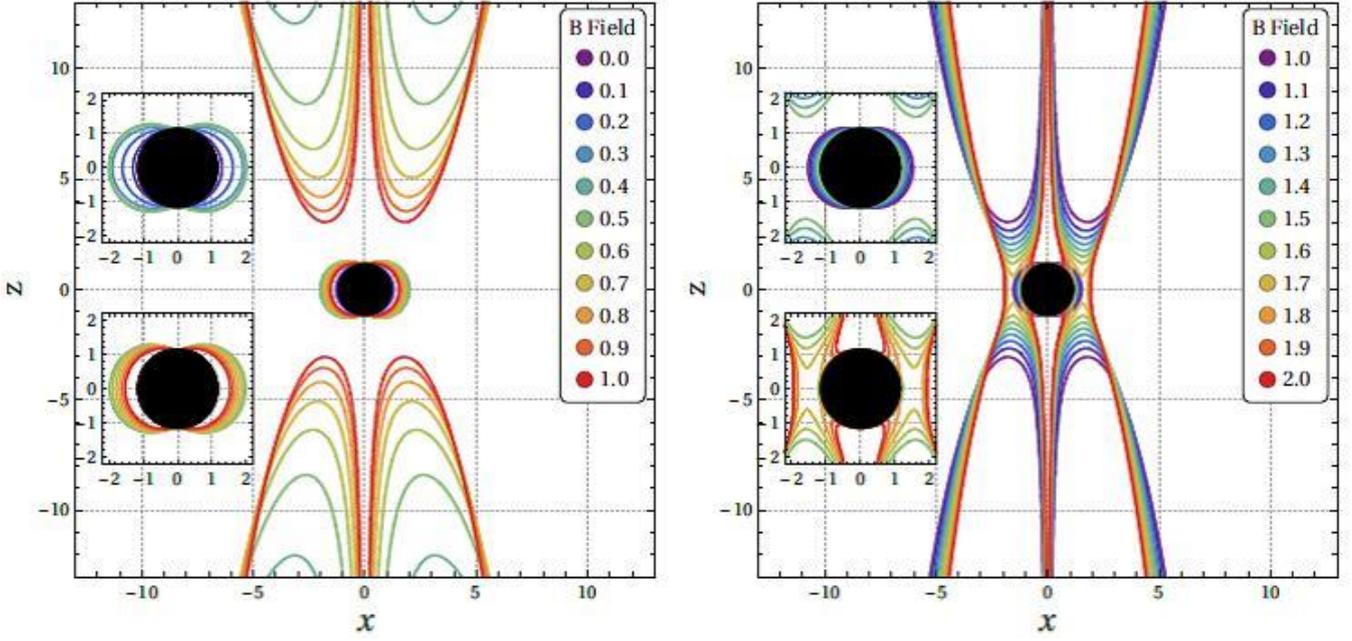


Fig. 5. For varying combinations of magnetic field B , the ergo region for the extremal axially symmetric magnetised black hole case is shown on the $x - z$ plane. In the left panel, the zoomed picture for cases when the magnetic field varies between 0 and 0.5 is shown in the upper inset plot. The lower inset plot, on the other hand, is a zoomed picture for cases when the magnetic field varies between 0.5 and 1.0. Similarly, in the right panel, the zoomed picture for cases when the magnetic field varies between 1.0 and 1.5 is shown in the upper inset plot. The lower inset plot, on the other hand, is a zoomed picture for cases when the magnetic field varies between 1.5 and 2.0.

It is well known that recent modern astronomical observations show that the outflows that can have energies in the range of $E \approx 10^{42} - 10^{47}$ erg/s from active galactic nuclei (AGN) in the form of winds and jets have been observed via X -ray, γ -ray and Very Long Baseline Interferometry (VLBI) observations. There is the relevance of the charged particle motion with these particle outflows coming out from AGN. In this regard, one needs to explore Penrose process to propose an explanation for these observations. Thus, we turn to discuss the energy efficiency that refers to the maximum energy extracted as the radiation due to the infalling matter into the ergoregion around the black hole. In the case of neutral $q_3 = 0$ and charged $q_3 \neq 0$ particles, the energy efficiency via the Penrose process can be defined by following expressions, respectively:

$$\eta|_{q_3=0} = \frac{1}{2(4+B^2(1+\sqrt{1-Q^2})^2)} \times \left[\left(-8BQ(1+\sqrt{1-Q^2}) \right) \times \left(4 - B^2(1+\sqrt{1-Q^2})^2 \right) + \left(4 + B^2(1+\sqrt{1-Q^2})^2 \right)^2 \right]^{1/2} - \left(4 + B^2(1+\sqrt{1-Q^2})^2 \right), \quad (28)$$

and

$$\eta = \eta|_{q_3=0} - \frac{q_3}{E_1} \left[-\frac{Q}{1+\sqrt{1-Q^2}} + \frac{3}{4}QB^2(1+\sqrt{1-Q^2}) \right]. \quad (29)$$

For further analysis we shall for simplicity consider $E_1/m_1 = 1$. In doing so, we can further assume that $q_3/E_1 = q/m$ at the splitting point occurring around black hole, especially very close to the black hole's horizon $r = r_+$. However, the location of the splitting point can also exist at a large distance from the black hole's horizon as the ergo region extends; see Fig. 5. In order to be more precise we shall restrict ourselves to the case for which the particle's splitting point occur in the close vicinity of the back hole's horizon.

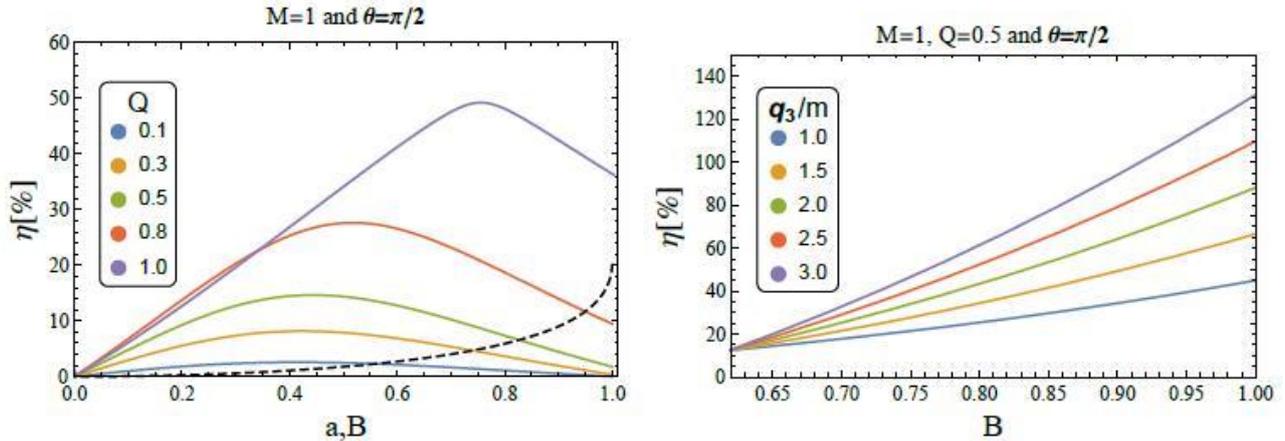


Fig. 6. Plot shows the energy efficiency as the function of B in the equatorial plane, $\theta = \pi/2$. **Left panel:** efficiency $\eta[\%]$ is plotted for various combinations of Q in the case with neutral particle, i.e. $q_3 = 0$. **Right panel:** efficiency $\eta[\%]$ is plotted for various combinations of q_3/m in the case of fixed $Q = 0.5$. Note that dashed line in the left panel shows the energy efficiency for rotating Kerr black hole.

We now analyze the energy efficiency, η , as the function of B for various combinations. In Fig. 6, we show the energy efficiency extracted from the magnetized black hole as that of the infalling mater into the ergoregion. The left panel shows the impact of the combined effect of black hole charge Q and magnetic field parameter B on the energy efficiency, while the right panel shows the same behavior for fixed $Q = 0.5$ in the case with the charged particle that refers to the escaping piece of massive particle falling into the ergosphere. As shown in Fig. 6 (left panel), the shape of the energy efficiency shifts up to higher η with increasing Q . However, it slightly gets decreased as the magnetic field parameter B increases. This happens because the area of the egrosphere required for energy extraction turns out to be getting smaller beyond $B > B_{cr}$; see Fig 6. It is worth noting that the maximum value of the efficiency reaches up to the value greater than 50 % which is comparable value for Kerr black hole case. This is a remarkable property of the axially symmetric magnetized Reissner-Nordström black hole. As stated above we show the energy efficiency for neutral particle, i.e. $q_3 = 0$ in the left panel, whereas in the right panel we show that energy efficiency can exceed 100 % in the case of charged particle $q_3 \neq 0$.

CONCLUSION

The main results and conclusions of the dissertation “Evolution and dynamics of compact astrophysical objects in relativistic theories of gravity” are presented below:

1. The processes of black hole formation in higher dimensions has been studied, and it has been shown that stable circular orbits cannot exist for accretion disk to form, i.e., bound orbits/ISCO do not exist around higher dimensional black holes in Einstein gravity and hence a rotating black hole cannot be formed in higher dimensions $D > 4$.

2. Circular orbits around higher dimensional rotating pure Gauss–Bonnet (GB) black holes have been studied, and it has been shown that the only circular orbits that could occur are all unstable and their radius is bounded from the below by that of the photon circular orbit and bound and stable circular orbits do exist for pure GB/Lovelock rotating black holes in dimensions, $2N + 2 \leq D \leq 4N$. It has been concluded that higher dimensional rotating black holes in Einstein gravity cannot be formed by gravitational collapse/accretion and they could however be formed only in pure GB/Lovelock gravity.

3. A general formalism for testing cosmic censorship conjecture by studying the process of overspinning a rotating black hole in higher dimensions has been developed, and it has been shown that the weak cosmic censorship conjecture is always obeyed even under linear accretion process in $D > 5$.

4. Both extremal and near-extremal (2+1) dimensional BTZ black holes in Einstein and Einstein-Gauss-Bonnet theories of gravity have been studied, respectively, and it has been shown that they can be overcharged in both theories of gravity, thus resulting in not obeying the weak cosmic censorship conjecture.

5. A new formalism by studying the influence of perfect fluid dark matter on dynamics of particle motion, energy efficiency extracted from black holes as well as black hole dynamics have been developed. It has been shown that the combined effects of dark matter and magnetic field can mimic the black hole rotation parameter up to $a/M \approx 0.8$. Following the developed model, the upper and lower ranges of perfect fluid dark matter have been estimated, i.e., it would be of the order $\lambda \sim (10^{-21} - 10^{-20})$ for the Sgr A * and $\lambda \sim (10^{-12} - 10^{-11})$ for the galaxy M87.

6. A formalism by studying the combined effects of perfect fluid dark matter and cosmological constant together has also been presented and developed. The analytical expressions for a certain threshold limit for which a repulsive effect due to the cosmological constant dominates over the attractive effect of the perfect fluid dark matter has been obtained. It has also been shown that the RN-dS black hole cannot be overcharged beyond a certain threshold limit, and hence the weak cosmic censorship conjecture is strongly respected.

7. The novel and qualitative aspects of the axially symmetric magnetized of the axially symmetric magnetized black hole spacetime and the effect of its magnetic field on the efficiency of the energy through the Penrose process for both

neutral and charged particles have been studied, and it has been shown that the magnetized Reissner-Nordström black hole would be a big energy reservoir as a Kerr black hole with angular momentum. It has interestingly been observed that even for the case of neutral particle the efficiency of the Penrose process for the extremal ($Q = M$) case of the axially symmetric magnetized Reissner-Nordström is more than double ($\approx 50\%$) to that of the extremal Kerr ($a = M$) black hole case which is about $\approx 20\%$.

**НАУЧНЫЙ СОВЕТ DSc.03/31.03.2022.T/FM.10.04 ПО ПРИСУЖДЕНИЮ
УЧЕНОЙ СТЕПЕНЕЙ ПРИ ИНСТИТУТЕ ФУНДАМЕНТАЛЬНЫХ И
ПРИКЛАДНЫХ ИССЛЕДОВАНИЙ НАЦИОНАЛЬНОГО
ИССЛЕДОВАТЕЛЬСКОГО УНИВЕРСИТЕТА “ТИИИМСХ”**

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ШАЙМАТОВ САНЖАР РУЗИМУРOTOVИЧ

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ВВЕДЕНИЕ (аннотация к диссертации доктора наук (DSc))

Актуальность и востребованность темы диссертации. Благодаря современным астрономическим наблюдениям, обнаружению гравитационных волн от слияния черных дыр в тесных двойных системах и наблюдению теней сверхмассивных черных дыр M87 и Стрелец A, появилась реальная возможность экспериментально исследовать природу геометрии пространства-времени и феномен гравитационного взаимодействия в режиме сильного поля. Эти недавние наблюдения предоставили веские доказательства в пользу существования черных дыр в природе и, как ожидается, станут очень мощными тестами для исследования неизвестных аспектов, связанных с точными измерениями параметров черных дыр. Несмотря на это, текущие прямые и косвенные астрономические наблюдения не объясняют природу и образование черных дыр в более высоких измерениях, т.е. размерностью пространства $D > 4$. Тогда возникает вопрос, что происходит и как образуются вращающиеся черные дыры в более высоких измерениях? Кроме того, теория гравитации Эйнштейна ограничена, например, из-за её неприменимости к физической сингулярности, которая осталась одним из важнейших нерешенных вопросов, как граница классической теории, где она теряет свою применимость. Все это, в свою очередь, приводит к необходимости новых моделей и альтернативных теорий гравитации для решения вышеупомянутых оставшихся без ответа вопросов общей теории относительности.

В последние годы в нашей республике большое внимание уделяется развитию экспериментальных и фундаментальных исследований в области релятивистской астрофизики. Наблюдательные и теоретические исследования получили поддержку в развитии науки по всем направлениям в нашей стране. Эти исследования играют значительную роль в области релятивистской астрофизики и нашли отражение в Стратегии действий по дальнейшему развитию Республики Узбекистан на 2017-2021 годы. В итоге можно отметить, что теоретическая и релятивистская астрофизика гравитационных компактных объектов развивалась путем проведения в республике научных исследований на высоком международном уровне, т.е. исследования оптических и энергетических свойств астрофизических черных дыр, голых сингулярностей и проверке решений для черных дыр по динамике частиц в различных ситуациях при исследовании новых эффектов общей теории относительности. Стоит отметить, что вследствие развития релятивистской астрофизики в республике, в стране зарождаются новые научные направления, так как перед учеными стоят серьезные задачи в разработке качественных аспектов природы компактных гравитационных объектов.

Данная диссертационная работа соответствует задачам, утвержденным в государственных нормативных документах и в Указе Президента Республики Узбекистан №УП-4947 «О стратегии действий по дальнейшему

развитию Республики Узбекистан» от 7 февраля и в «Дорожная карта основных направлений структурных реформ в Узбекистане на 2019-2021 годы» от 29 ноября 2018 года и др.

Соответствие исследования приоритетным направлениям развития науки и технологий республики.

Диссертационное исследование выполнено в соответствии с приоритетным направлением развития науки и технологий Республики Узбекистан II. «Энергетика, энерго- и ресурсосбережение».

Обзор международных научных исследований по теме диссертации. Исследование формирования и динамики черных дыр и проверка устойчивости горизонта черной дыры путем погружения в поля материи и частиц в режиме сильного поля в различных моделях гравитации, исследования моделирования поля темной материи на динамике черных дыр и исследования энергетических свойств черных дыр проводятся различными ведущими исследовательскими центрами и учреждениями, такими, как Институт гравитационной физики им. Макса Планка (Германия), Франкфуртский университет (Германия), Межуниверситетский центр астрономии и астрофизики (Индия), Калифорнийский технологический институт (США), Чикагский университет (США), Восточно-средиземноморский университет (Турция), Институт теоретической физики (Китай), Научно-исследовательский центр физики и полупроводников (Республика Корея), Институт фундаментальных исследований Тата (Индия), Силезский Университет в Опаве (Чехия), Назарбаев Университет (Казахстан), Университет Фудань (Китай), Астрономический институт Улугбека (Узбекистан) и Институт фундаментальных и прикладных исследований (Узбекистан) и др.

В эволюции черной дыры существуют два основных процесса: коллапс облака материи под действием собственной гравитации и аккреция материи на уже существующий центр притяжения. Необходимое условие для того, чтобы оба процесса работали, состоит в том, что общая сила, воздействующая на схлопывающиеся элементы жидкости или на пробные срастающиеся частицы, должна быть притягивающей. Оказывается, это имеет место в обычных четырех измерениях для коллапсирующей или аккрецирующей материи, имеющей ненулевой угловой момент. Тогда возникает вопрос, что происходит в более высоких измерениях, превышающих обычные четыре? С этой точки зрения все более важную роль играет более глубокое понимание новых и качественных аспектов черных дыр, то есть того, могут ли как гравитационный коллапс, так и аккреция работать для образования вращающихся черных дыр в более высоких измерениях. Тогда можно предсказать, что тогда и только тогда, когда оба эти процесса не действуют в более высоких измерениях, образуя вращающуюся черную дыру, и тогда их эффект может также отражаться в том факте, что гипотеза о слабой космической цензуре всегда выполняется даже при линейном процессе аккреции при размерностях пространства $D > 5$.

В этой ситуации чистая гравитация Лавлока может занять центральное место и дать нам возможность проверить, могут ли оба вышеупомянутых процесса работать для образования черных дыр или нет в более высоких измерениях.

Степень изученности проблемы. По степени изученности проблемы многие ученые из различных научных центров и учреждений, т. е. индийские ученые (Н. Дадич, П. Джоши, А. Мишра, С. Саркар, М. Патил, Р. Гош и др.), японские ученые (И. Такахиса, Х. Томохиро, К. Масаши), итальянские ученые (К. Бамби, Л. Модесто, Д. Малафарина, О. Занотти), чешские ученые (З. Стухлик, М. Колос, Я. Шее, Й. Ковар, В. Карась), немецкие ученые (К. Лаеммерцаль, Л. Реццолла, Ю. Кунц, Э. Хакманн, Д. Кунст, В. Перлик), китайские ученые (Б. Чен, Дж. Цзян, Б. Ге), ученые Республики Корея (Б. Гвак) и другие провели теоретические и наблюдательные исследования образования черных дыр и устойчивости горизонтов черных дыр, проверяя гипотезу о космической цензуре (WCCC) в различных теориях гравитации. Однако эти проблемы еще не были полностью исследованы для черных дыр в более высоких измерениях $D > 4$ как в теории гравитации Эйнштейна, так и в чистой теории гравитации Лавлока.

Недавние исследования и наблюдения показывают, что существует связь движения заряженных частиц с потоками частиц, исходящими из активных ядер галактик (АЯГ). В связи с этим с тех пор был разработан обширный анализ в самых разнообразных ситуациях многими учеными, в том числе индийскими (М. Ваг, С. Дурандар, Н. Дадич), чешскими (З. Стухлик, М. Колос и др.), украинскими (О. Заславский), итальянскими (Д. Малафарина, Э. Бараус), узбекскими (Б. Ахмедов и др.), канадскими (В. Фролов и др.) и многими другими, посвященные влиянию магнитного поля на механизмы извлечения энергии из черных дыр и аккреционных дисков. Однако ни в одном из этих исследований не рассматривалось решение намагниченной черной дыры, которое создает аксиально-симметричное пространство-время из-за существования магнитного поля даже без какого-либо вращения.

Связь темы диссертации с научно-исследовательскими работами научно-исследовательского учреждения, где выполнена диссертация. Диссертационное исследование выполнено на период 2021-2022 гг. в рамках научных проектов Института фундаментальных и прикладных исследований национального исследовательского университета “ТИИИМСХ” и Астрономического института Академии наук Узбекистана: Ф-ФА-2021-432 «Анализ и обработка данных со спутников для маломассивных рентгеновских двойных систем» (2021-2026 гг.).

Целью исследования является разработка теоретического формализма, который приводит к подробному описанию образования черной дыры и его влияния на стабильность горизонта черной дыры в более высоких измерениях $D > 4$, влияние темной материи идеальной жидкости на динамику частиц и черные дыры в различных ситуациях, качественные аспекты природы намагниченной черной дыры Рейсснера-Нордстрема, являющейся большим резервуаром энергии из-за расширения эрго-области, а также

астрофизическое приложение полученных результатов к распределениям темной материи, которые существуют в центре галактик, к ограничению достоверности альтернативных моделей черных дыр и к описанию высоких энергий от АЯГ при объяснении астрофизических наблюдений.

Задачи исследования:

изучить образование вращающихся черных дыр в более высоких измерениях в результате процессов аккреции, в которых материя вращается вокруг тяготеющего центра по устойчивым круговым орбитам;

изучить стабильные круговые орбиты (СКО) частиц вокруг черных дыр в высших измерениях в теории Эйнштейна и чистой гравитации Лавлока; разработать общий формализм для проверки гипотезы о космической цензуре путем изучения процесса чрезмерного вращения/перезарядки вращающейся черной дыры в более высоких измерениях $D > 4$ и низких измерениях $D < 4$ как для линейного, так и для нелинейного режима аккреции частиц;

изучить влияние идеально жидкой темной материи на динамику движения частиц вокруг черных дыр в различных теориях гравитации;

оценить величину идеально жидкой темной материи по ее распределению в центре галактик Sgr A и M87;

изучение геометрии аксиально-симметричного пространства-времени намагниченной черной дыры и описание эффективности использования энергии посредством процесса Пенроуза как для нейтральных, так и для заряженных частиц.

Объектом исследования являются процессы эволюции черных дыр в высших измерениях, идеально жидкая темная материя, электромагнитные и гравитационные поля в среде, окружающей астрофизические черные дыры в различных теориях гравитации.

Предметом исследования являются формирование черной дыры, ее динамика, а также проверка стабильности горизонта черной дыры в более высоких измерениях, влияние темной материи идеальной жидкости на астрофизические процессы, связанные с данными наблюдений, а также эффективность извлечения энергии в аксиально-симметричном пространстве-времени намагниченной черной дыры.

Методами исследования являются математический аппарат общей теории относительности и метрической аффинной дифференциальной геометрии, а также аналитические и численные методы решения дифференциальных уравнений динамики частиц и полей.

Научная новизна исследования заключается в следующем:

впервые изучены процессы образования черных дыр в более высоких измерениях; показано, что для гравитации Эйнштейна не может существовать стабильных круговых орбит для образования аккреционного диска, и, следовательно, не может образоваться вращающаяся черная дыра в более высоких измерениях $D > 4$;

впервые разработан общий формализм для проверки гипотезы о космической цензуре путем изучения процесса чрезмерного вращения вращающейся черной дыры в более высоких измерениях; показано, что гипотеза о слабой космической цензуре всегда выполняется даже при линейном процессе аккреции в $D > 5$;

впервые показано, что экстремальные и почти экстремальные $(2 + 1)$ размерные черные дыры BTZ могут быть перезаряжены как в теории гравитации Эйнштейна, так и в теории гравитации Эйнштейна-Гаусса-Бонне, что приводит к неподчинению гипотезе слабой космической цензуры;

впервые развит формализм, изучая влияние идеально жидкой темной материи на динамику движения частиц и эффективность извлечения энергии из черных дыр, а также из динамики черных дыр; было показано, что с наблюдательной точки зрения далекие наблюдатели не смогут отличить керровскую черную дыру в вакууме от черной дыры с большим угловым моментом, погруженной в оболочку из темной материи с внешним магнитным полем;

впервые представлен формализм, изучая комбинированные эффекты идеально жидкой темной материи и космологической постоянной вместе; было показано, что черная дыра RN-dS не всегда может быть перезаряжена сверх определенного порогового предела, при котором отталкивающий эффект, возникающий из-за космологической постоянной, преобладает над притягивающим, обусловленным идеально жидкой темной материей;

впервые представлено изучение геометрии, новых и качественных аспектов пространства-времени аксиально-симметричной намагниченной черной дыры и влияния ее магнитного поля на эффективность использования энергии посредством процесса Пенроуза как для нейтральных, так и для заряженных частиц; было показано, что намагниченная черная дыра Рейсснера-Нордстрема будет большим резервуаром энергии, как черная дыра Керра с угловым моментом.

Практические результаты исследования заключаются в следующем:

доказано, что в гравитации Эйнштейна не могут существовать стабильные круговые орбиты, для формирования аккреционного диска в более высоких измерениях, и следовательно, вращающаяся черная дыра не может образоваться при $D > 4$;

показано, что отсутствие стабильных круговых орбит может быть отражено в том факте, что вращающиеся черные дыры не могут быть перекручены даже при линейном процессе аккреции при $D > 5$;

показано, что комбинированные эффекты темной материи и магнитного поля могут имитировать параметр вращения черной дыры с точностью до $a/M \approx 0.8$; в соответствии с разработанной моделью были оценены верхний и нижний диапазоны идеально жидкой темной материи, т.е. она будет порядка $\lambda \sim (10^{-21} - 10^{-20})$ для Sgr A* и $\lambda \sim (10^{-12} - 10^{-11})$ для галактики M87;

получены аналитические выражения для определенного порогового предела, при котором эффект отталкивания, обусловленный космологической постоянной, доминирует над эффектом притяжения идеально жидкой темной материи; продемонстрировано, что за пределами этого порогового предела черная дыра Райснера-Нордстрема не может иметь избыточный заряд, и следовательно, гипотеза о слабой космической цензуре строго выполняется;

обнаружено, что даже для случая нейтральной частицы эффективность процесса Пенроуза для экстремального ($Q=M$) случая аксиально-симметричной намагниченной черной дыры Рейснера-Нордстема, более чем вдвое ($\approx 50\%$) превышает эффективность экстремального случая черной дыры Керра ($a=M$), который составляет около 20 % .

Достоверность результатов исследования обосновывается использованием новых методов общей теории относительности и современных численных методов и алгоритмов; проведенной тщательной проверкой согласованности полученных результатов с современными астрономическими наблюдениями и результатами других авторов; выводами, хорошо согласующимися с общими принципами компактных гравитационных объектов. Это подтверждается фактами, что в диссертационной работе использовались стандартные методы общей теории относительности, а также методы математической и теоретической физики с современными численными методами и программами; полученные теоретические результаты были сопоставлены путем проверки с имеющимися теоретическими данными и современными астрономическими наблюдениями и результатами других ученых; приведенные выводы результатов хорошо согласуются с общими принципами теории поля компактных гравитационных объектов в режиме сильной гравитации.

Научная и практическая значимость результатов исследования. Научная значимость результатов исследования в диссертации состоит в разработке формализмов для анализа образования вращающихся черных дыр и проверки гипотезы о космической цензуре путем изучения процесса быстро вращающихся черных дыр с аккрецией частиц для получения общей информации и убедительных математических доказательств, чтобы глубже понять новые и качественные аспекты образования вращающихся черных дыр в более высоких измерениях $D > 4$. Кроме того, частицы с высокой энергией образуются в результате столкновений в аккреционном диске, и яркость диска зависит от лежащей в его основе геометрии. Однако в реалистичном сценарии объект нельзя считать находящимся в вакууме, поскольку известно, что распределения темной материи существуют в центре галактик. Кроме того, магнитные поля играют важную роль в динамике заряженных частиц вокруг черных дыр, особенно вблизи горизонта черной дыры. Поэтому, чтобы быть уверенным в выводах, сделанных на основе наблюдений аккреционных дисков, важно изучить влияние, которое

присутствие полей внешней материи и магнитных полей оказывает на частицы в дисках.

Практическая значимость результатов диссертации заключается в фактах, которые, с точки зрения наблюдений, полученные результаты свидетельствуют о том, что определения ВСКО по наблюдению электромагнитного излучения, испускаемого аккреционным диском, может быть недостаточно для установления значения углового момента источника. Фактически, удаленные наблюдатели не смогли бы отличить черную дыру Керра в вакууме от черной дыры с меньшим угловым моментом и погруженной в поле темной материи, а также от намагниченной черной дыры с большим угловым моментом. Таким образом, эти теоретические исследования в диссертации могут помочь ограничить обоснованность альтернативных моделей черных дыр при объяснении астрофизических наблюдений. Также теоретический анализ верхнего и нижнего диапазонов распределения идеальной текучей темной материи вокруг сверхмассивных черных дыр может быть использован для анализа природы и динамики поля темной материи при разработке данных наблюдений с помощью сигналов, которые поступают далеко от гравитационных объектов при взаимодействии с промежуточными веществами. Полученные результаты относительно энергетической эффективности, извлеченной из аксиально-симметричного намагниченного пространства-времени черной дыры, могут быть полезны при анализе астрономических наблюдений, связанных с оттоками, имеющими большие энергии, от активных галактических ядер в виде ветров и струй. Результаты, связанные с анализом особых аспектов черных дыр в более высоких измерениях, могут быть использованы в качестве принятой модели для разработки дальнейших методов и объяснения эволюции вращающихся черных дыр в более высоких измерениях во Вселенной.

Внедрение результатов исследования. На основе полученных результатов по исследованиям эволюции и динамики компактных астрофизических объектов в релятивистских теориях гравитации:

результаты теоретических исследований и методы по круговым орбитам вокруг вращающихся черных дыр Эйнштейна и Гаусса-Бонне высших измерений и образованию черных дыр были использованы в рамках программ Межуниверситетского центра астрономии и астрофизики, поддерживаемых Комиссией по университетским грантам (письмо Межуниверситетского центра астрономии и астрофизики, Индия, от 25 ноября 2022 года), а также рядом зарубежных авторов (Physics of the Dark Universe, Vol. 35, id. 100916, 2022; Physical Review D, Vol. 105, id. 124033, 2022; Classical and Quantum Gravity, Vol. 38, id. 155017, 2021) для изучения движения фотона и его тени вокруг вращающейся заряженной черной дыры в гравитации 4D ЭГБ и стабильных круговых орбит вокруг статических черных дыр Эйнштейна-Гаусса-Бонне и т.д. с использованием аналитических и численных расчетов;

научные результаты о быстро вращающихся черных дырах в более высоких ($D > 4$) и низких ($2+1$) измерениях были использованы несколькими зарубежными учеными (Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 077, 2022; Physical Review Research, Vol. 4, id. 023031, 2022; The European Physical Journal C, Vol. 81, id. 1131, 2021; Physics of the Dark Universe, Vol. 32, id. 100831, 2021; Journal of High Energy Physics, Vol. 2021, id. 45, 2021; The European Physical Journal C, Vol. 81, id. 49, 2021) при разработке различных моделей, связанных со стабильностью горизонта в различных гравитационных моделях. Применение результатов, полученных в диссертации, позволило бы разработать фундаментальные теории проверки устойчивости горизонта в других гравитационных моделях;

результаты исследования влияния идеально жидкой темной материи на движение частиц вокруг статической черной дыры, погруженной во внешнее магнитное поле, и комбинированные эффекты идеально жидкой темной материи и космологической постоянной были использованы несколькими зарубежными исследователями (Physics Letters B, Vol. 829, id. 137031, 2022; Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 077, 2022; Journal of Cosmology and Astroparticle Physics, Vol. 2021, id. 012, 2021; Physical Review D, Vol. 104, id. 084015, 2021; Journal of Cosmology and Astroparticle Physics, Vol. 2022, id. 043, 2022; Universe, Vol. 8, id. 369, 2022; Physical Review D, Vol. 103, id. 104070, 2021; Communications in Theoretical Physics, Vol. 73, id. 095403, 2021; The European Physical Journal C, Vol. 81, id. 269, 2021) для разработки формализма регулярной неминимальной магнитной черной дыры как источника квазипериодических колебаний, исследования компонентов темной материи с миллизарядом из силуэта и энергии черной дыры RN-AdS погруженной в идеально жидкую темную материю, при расширении Джоуля-Томсона, в различных гравитационных моделях;

результаты, посвященные выявлению качественных аспектов геометрии пространства-времени аксиально-симметричной намагниченной черной дыры и ее магнитного поля для выявления ее влияния на астрофизические явления и эффективность извлеченной энергии, были использованы в рамках исследовательского гранта Института физики и математики Университета Мичоакана № CF-MG-2558591 FORDECYT-PRONACES CONACYT (письмо Института физики и математики Университета Мичоакана в Сан-Николас-де-Идальго, Мексика), а также ряда зарубежных исследователей (Physical Review D, Vol. 105, id. 064072, 2022; International Journal of Modern Physics A, Vol. 37, id. 2250144, 2022; The European Physical Journal Plus, Vol. 137, id. 645, 2022; Universe, Vol. 8, id. 571, 2022; The European Physical Journal Plus, Vol. 136, id. 1032, 2021; The European Physical Journal C, Vol. 81, id. 983, 2021; Physical Review D, Vol. 104, id. 064016, 2021; Galaxies, Vol. 9, issue 4, id. 71, 2021; Galaxies, Vol. 9, id. 63, 2021) для разработки теоретического исследования динамики заряженных частиц в области квантово-скорректированных статических черных дыр и гравитационного аналога вращения Фарадея в намагниченном пространстве-времени Керра и RN и т. д.

Апробация результатов исследования. Результаты исследований были представлены и обсуждены на 3 международных и республиканских научных конференциях.

Опубликованность результатов исследования. По теме диссертационной работы опубликованы 23 научных работ, из них 20 статей в научных журналах, рекомендованных Высшей аттестационной комиссией Республики Узбекистан для публикации основных научных результатов докторских диссертаций, в том числе 19 в международных научных журналах.

Объем и структура диссертации. Диссертация состоит из введения, четырех глав, заключения и списка литературы. Объем диссертации составляет 218 страниц.

ЗАКЛЮЧЕНИЕ

По результатам исследования, проведенного по теме диссертации доктора наук (DSc) «Эволюция и динамика компактных астрофизических объектов в релятивистских теориях гравитации», представлены следующие выводы.

1. Исследованы процессы образования черной дыры в более высоких измерениях, и показано, что стабильные круговые орбиты не могут существовать для формирования аккреционного диска, т.е. связанные орбиты/ISCO не существуют вокруг черных дыр более высоких измерений в гравитации Эйнштейна, и, следовательно, вращающаяся черная дыра не может быть сформирована в более высоких измерениях $D > 4$.

2. Исследованы круговые орбиты вокруг вращающихся черных дыр, которые имеют метрику чистого Гаусса–Бонне (GB) более высокого измерения, и показано, что все круговые орбиты, которые могут возникнуть, нестабильны, и их радиус ограничен снизу радиусом круговой орбиты фотона, а связанные и стабильные круговые орбиты существуют для вращающихся черных дыр GB/Лавлок, с размерностями $2N+2 \leq D \leq 4N$. Доказано, что вращающиеся черные дыры более высокой размерности в гравитации Эйнштейна не могут быть образованы гравитационным коллапсом/аккрецией, они могут образоваться только в чистой гравитации GB/Лавлока.

3. Разработан общий формализм для проверки гипотезы космической цензуры путем изучения процесса быстро вращающейся черной дыры в более высоких измерениях, и показано, что гипотеза слабой космической цензуры всегда выполняется даже при линейном процессе аккреции в $D > 5$.

4. Изучены как экстремальные, так и околоэкстремальные $(2+1)$ размерные черные дыры BTZ в теориях гравитации Эйнштейна и Эйнштейна-Гаусса-Бонне соответственно, и показано, что они могут иметь

сверхвысокий заряд в обеих теориях гравитации, что приводит к несоблюдению гипотезы слабой космической цензуры.

5. Разработан новый формализм, изучающий влияние идеально жидкой темной материи на динамику движения частиц, эффективность извлечения энергии из черных дыр, а также динамику черных дыр. Было показано, что комбинированное воздействие темной материи и магнитного поля может имитировать параметр вращения черной дыры с точностью до $a/M \approx 0.8$. Следуя разработанной модели, были оценены верхний и нижний диапазоны идеально жидкой темной материи, т.е. она была бы порядка $\lambda \sim (10^{-21} - 10^{-20})$ для Sgr A* и $\lambda \sim (10^{-12} - 10^{-11})$ для галактики M87.

6. Также представлен и развит формализм, основанный на изучении комбинированных эффектов идеально жидкой темной материи и космологической постоянной вместе взятых. Получены аналитические выражения для определенного порогового предела, при котором эффект отталкивания, обусловленный космологической постоянной, доминирует над эффектом притяжения идеально жидкой темной материи. Также было показано, что черная дыра РН не может быть заряжена сверх определенного порогового значения, и, следовательно, гипотеза о слабой космической цензуре строго соблюдается.

7. Изучены новые и качественные аспекты пространства-времени аксиально-симметричной намагниченной черной дыры и влияние ее магнитного поля на эффективность извлечения энергии с помощью процесса Пенроуза как для нейтральных, так и для заряженных частиц, и показано, что намагниченная черная дыра Рейсснера-Нордстрема была бы большим энергетическим резервуаром в виде черной дыры Керра с угловым моментом. Интересно было замечено, что даже для случая нейтральной частицы эффективность процесса Пенроуза для экстремального ($Q = M$) случая аксиально-симметричной намагниченной черной дыры Рейсснера-Нордстема более чем вдвое ($\approx 50\%$) превышает эффективность экстремального случая черной дыры Керра ($a = M$), который составляет около 20 %.

E'LON QILINGAN ISHLAR RO'YXTI
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“Fan va innovatsiyalar” xalqaro ilmiy jurnali (International scientific journal “Science and Innovation”) tahririyatida tahrirdan o‘tkazilib, o‘zbek, ingliz va rus tillaridagi matnlar o‘zaro muvofiqlashtirildi (07.12.2022).

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