“TIQXMMI” MILLIY TADQIQOT UNIVERSITETI HUZURIDAGI FUNDAMENTAL VA AMALIY TADQIQOTLAR INSTITUTI HUZURIDAGI ILMIY DARAJALAR BERUVCHI DSc.03/31.03.2022.T/FM.10.04 RAQAMLI ILMIY KENGASH

O‘zR FA ASTRONOMIYA INSTITUTI

KURBONOV NURIDDIN ABDURASHIDOVICH

ZARYADLANGAN QORA O‘RALAR ATROFIDA ZARYADLANGAN ZARRACHALAR DINAMIKASI VA ENERGETIK JARAYONLAR

01.03.01-Astronomiya
01.03.02-Astrofizika va Kosmos fizikasi

FIZIKA-MATEMATIKA FANLARI BO‘YICHA
FALSAFA DOKTORI (PhD)
DISSERTATSIYASI AVTOREFERATI

Toshkent – 2024

UDK: 524.882 (530.12)

Fizika-matematika fanlari bo‘yicha falsafa doktori (PhD) dissertatsiyasi avtoreferati mundarijasi

Content of the dissertation abstract of the doctor of philosophy (PhD) on physical and mathematical sciences

Оглавление автореферата диссертации доктора философии (PhD) по физико-математическим наукам

“TIQXMMI” MILLIY TADQIQOT UNIVERSITETI HUZURIDAGI FUNDAMENTAL VA AMALIY TADQIQOTLAR INSTITUTI HUZURIDAGI ILMIY DARAJALAR BERUVCHI DSc.03/31.03.2022.T/FM.10.04 RAQAMLI ILMIY KENGASH

O‘zR FA ASTRONOMIYA INSTITUTI

KURBONOV NURIDDIN ABDURASHIDOVICH

ZARYADLANGAN QORA O‘RALAR ATROFIDA ZARYADLANGAN ZARRACHALAR DINAMIKASI VA ENERGETIK JARAYONLAR

01.03.01-Astronomiya
01.03.02-Astrofizika va Kosmos fizikasi

FIZIKA-MATEMATIKA FANLARI BO‘YICHA FALSAFA DOKTORI (PhD) DISSERTATSIYASI AVTOREFERATI

Toshkent – 2024

Fizika-matematika fanlari bo‘yicha falsafa doktori (PhD) dissertatsiyasi mavzusi O‘zbekiston Respublikasi Vazirlar Mahkamasi huzuridagi Oliy attestatsiya komissiyasida B2024.2.PhD/FM1082. raqami bilan ro‘yxatga olingan.

Dissertatsiya O‘zbekiston Respublikasi Fanlar akademiyasi Ulug‘bek nomidagi Astronomiya institutida bajarilgan.

Dissertatsiya avtoreferati uch tilda (o‘zbek, ingliz, rus (xulosa)) Ilmiy kengashning veb-sahifasida (https://www.ifar.uz) va “ZiyoNet” Axborot ta’lim portalida (http://www.ziyonet.uz) joylashtirilgan.

Ilmiy rahbarlar:	**Toshmatov Bobir Abdumanonovich** fizika-matematika fanlari doktori
	Rayimbaev Djavlanbek Radjapbayevich fizika-matematika fanlari doktori
Rasmiy opponentlar:	**Atamurotov Farrux Shuxratovich** fizika-matematika fanlari doktori
	Jo‘rayeva Nozima Bobomurod qizi fizika-matematika fanlari bo‘yicha falsafa doktori
Yetakchi tashkilot:	**Al-Farobiy nomidagi Qozoq milliy universiteti**

Dissertatsiya himoyasi “TIQXMMI” Milliy tadqiqot universiteti huzuridagi fundamental va amaliy tadqiqotlar instituti huzuridagi DSc.03/31.03.2022.T/FM.10.04 raqamli Ilmiy kengashning 20__ yil “____” ____ soat ____ dagi majlisida bo‘lib o‘tadi (Manzil: 100000 Toshkent shahri, Qori Niyoziy ko‘chasi, 39-uy, Fundamental va amaliy tadqiqotlar instituti. 108-katta majlislar zali; tel.: (+99871) 237-09-61; faks: (+998 71) 234-09-62; e-mail: info@ifar.uz).

Dissertatsiya bilan “TIQXMMI” Milliy tadqiqot universiteti huzuridagi fundamental va amaliy tadqiqotlar instituti Axborot-resurs markazida tanishish mumkin (___ raqami bilan ro‘yxatga olingan). Manzil: 100000 Toshkent shahri, Qori Niyoziy ko‘chasi, 39-uy, Fundamental va amaliy tadqiqotlar instituti, 108-katta majlislar zali; tel.: (+99871) 237-09-61.

Dissertatsiya avtoreferati 20__ yil “ ___ ” ___ kuni tarqatildi.
(2024 yil “ ___ ” ____ dagi ___ -raqamli reyestr bayonnomasi)

B.J.Ahmedov
Ilmiy darajalar beruvchi ilmiy kengash raisi,f.-m.f.d., akademik.

Sh.N.Mardonov
Ilmiy darajalar beruvchi ilmiy kengash ilmiy kotibi f.-m.f.d. (DSc)

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

KIRISH (falsafa doktori dissertatsiyasi annotatsiyasi)

Dissertatsiya mavzusining dolzarbligi va zarurati. Zaryadlangan qora oʻralar sohasida zaryadlangan zarrachalar va ularning dinamikasini oʻrganish zamonaviy astrofizika va fundamental fizikada oʻta dolzarb va muhim tadqiqot sohasidir. Reissner-Nordström va Kerr-Nyuman metrikalari kabi yechimlar bilan tavsiflangan zaryadlangan qora oʻralar ekstremal sharoitlarda tortishish, elektromagnit va inert kuchlarining oʻzaro taʼsirini oʻrganish uchun noyob laboratoriyani taʼminlaydi. Ushbu muhitlar ixcham obyektlar yaqinidagi materiya va nurlanishning xatti-harakatini tushunish va umumiy nisbiylik nazariyasidan potentsial ogʼishlarni, ayniqsa kuchli elektromagnit maydonlar mavjudligida, tekshirish uchun juda muhimdir.

Zarrachalarning tezlanishi va yuqori energiyali emissiyalarning paydo boʻlishi kabi energetik jarayonlarni oʻrganish astrofizik hodisalarga chuqur taʼsir koʻrsatadi. Koʻpgina kuzatilgan hodisalar, jumladan relativistik reaktivlar, gamma-sochilishlar va yuqori energiyali kosmik nurlar, zaryadlangan qora oʻralar atrofida zaryadlangan zarrachalar dinamikasiga asoslangan mexanizmlarni oʻz ichiga olishi mumkindir. Bundan tashqari, ushbu tadqiqotlar ekstremal sharoitlarda plazma fizikasini tushunishimizga yordam beradi, bu esa Event Horizon teleskopi va kosmik rentgen hamda gamma-nurlanish teleskoplari kabi ilgʼor kuzatuv obyektlaridan olingan ma'lumotlarni sharhlash uchun zarurdir.

Yuqoridagi mavzularni koʻrib chiqish orqali ushbu dissertatsiya ishida nazariy modellarni kuzatishlar bilan bogʼlash, qora oʻralar muhiti va ularning energetik signaturalari haqidagi tushunchalarimizni rivojlantirishga qaratilgan zamonaviy yondashuvga mos keladi. Bu ish nafaqat yuqori energiyali astrofizik jarayonlarga oid tushunchalarni mukammallashtirish, balki fundamental nazariyalarni ekstremal sharoitlarda sinab koʻrishning kengroq maqsadiga hissa qoʻshadi va bu uni nazariy va kuzatuv mulohozalarda juda dolzarb qiladi. Mamlakatimizda qora oʻralarning akkretsiya diskidagi nurlanish mexanizmlari hamda qora oʻra atrofidagi optik va energetik jarayonlarni oʻrganish, tortishish nazariyalarini nazariy oʻrganish va kuzatish maʼlumotlari asosida sinovdan oʻtkazishga katta eʼtibor qaratilmoqda.

Ushbu dissertatsiya ishi vazifalari tasdiqlangan davlat normativ hujjatlari, Oʻzbekiston Respublikasi Prezidentining 2017-yil 7-fevraldagi PQ-4947 “Oʻzbekiston Respublikasini yanada rivojlantirish uchun chora-tadbirlar strategiyasi toʻgʻrisida”gi farmoni va 2017-yil 18-fevraldagi PQ-2789-sonli “Fanlar akademiyasi faoliyati, ilmiy-tadqiqot ishlarini tashkil etish, boshqarish va moliyalashtirishni yanada takomillashtirish chora-tadbirlari toʻgʻrisida”gi qarori talablariga mos keladi.

Tadqiqotning respublika fan va texnologiyalari rivojlanishining ustuvor yoʻnalishlariga muvofiqligi. Dissertatsiya tadqiqot ishi Oʻzbekiston Respublikasi fan va texnikasining ustuvor yoʻnalishlariga muvofiq amalga oshirilgan.

Dissertatsiya mavzusi boʻyicha xalqaro ilmiy tadqiqotlar sharhi.

Dilaton maydonlari bilan yuqori oʻlchovli nazariyalardagi qora oʻralar Buyuk Britaniyalik fizik G.W. Gibbons va Yaponiyalik Kei-ichi Maeda (Nuclear Physics B, vol. 298) tomonidan oʻrganib chiqilgan. EMS qora oʻralari uchun yechimlar

Xitoylik olimlar S. Yu, J. Qiu, va C. Gao tadqiq qilingan (Classical and Quantum Gravity, Volume 38, Number 10).

Kalb-Ramond gravitatsiyasi doirasidagi ilk ish M. Kalb va P. Ramond tomonlaridan chop etilgan (Physical Review D, vol. 9, no. 8) va ushbu gravitatsiya doirasidagi qora oʻralar uchun yechimlar Xitoylik olimlar Z.-Q. Duan, J.-Y. Zhao, and K. Yang tadqiq qilingan (Eur. Phys. J. C 84, 798).

Energetik jarayonlar bir qator olimlar tomonidan oʻrganib chiqilgan - Penrouz jarayoni (Nuovo Cimento Rivista Serie, vol. 1, 1969), magnit Penrouz jarayoni (Mon. Not. R. Astron. Soc, vol. 478) va elektr Penrouz jarayoni (Phys. Rev. D, vol. 104, no. 8).

Muammoning oʻrganilganlik darajasi.

1969 yilda mashhur ingliz fizigi (hozirda Nobel mukofoti sovrindori) Rodjer Penrouz aylanuvchi qora oʻradan energiya ajratib chiqish jarayonini tavsiflovchi mexanizmni taklif qildi. Keyinchalik N.Dadhich “magnit Penrouz jarayoni” deb nomlangan energiya chiqarish mexanizmini taklif qildi. 2021 yilda Arman Tursunov elektr Penrouz jarayoniga oid maqola yozdi. Bu jarayonlarni oʻrganish Yevropada (R.Penrouz, Z.Stuxlik va M.Kolosh va boshqalar), Hindistonda (N.Dadhich, S.M.Vag, V.Dhurandhar va boshqalar) hamda dunyo tanigan olimlar tomonidan keng olib borildi. Respublikamizda turli tortishish nazariyalarida qora oʻralar atrofidagi optik va energetik jarayonlar haqidagi nazariy tadqiqotlar B.Ahmedov, A.Abdujabborov, J.Rayimboyev, A.Tursunov, S.Shaymatov va boshqalar tomonidan potentsial jihatdan oʻrganilgan. Ular oʻz tadqiqotlarida qora oʻralardan energiya ajralib chiqish mexanizmini oʻrganishda umumiy nisbiylik nazariyasi doirasida oʻrganishgan. Mening dissertatsiya ishimda bu jarayon gravitatsiyaning muqobil nazariyasida (Eynshteyn-Maksvell skalyar (EMS) nazariyasidagi va Kalb-Ramond (KR) gravitatsiyasidagi qora oʻralar) koʻrib chiqildi.

Dissertatsiya tadqiqotining dissertatsiya bajarilgan ilmiy-tadqiqot muassasasi ilmiy-tadqiqot ishlari rejalari bilan bogʻliqligi.

Dissertatsiya Ulugʻbek nomidagi Astronomiya instituti hamda Oʻzbekiston Fanlar akademiyasi Yadro fizikasi institutining F-FA-2021-510 “Modifikatsiyalangan gravitatsiyada neytron yulduzlarining yadroviy moddasini tekshirish” (2021-2026) ilmiy loyihalari doirasida bajarilgan.

Tadqiqotning maqsadi

energetik jarayonlar va qora oʻralar atrofida zaryadlangan zarrachalarning harakatini oʻrganishdan iborat.

Tadqiqotning vazifalari:

Eynshteyn-Maksvell-skalyar nazariyasida zaryadlangan qora oʻralar atrofida zaryadlangan zarralar dinamikasini oʻrganish;

Eynshteyn-Maksvell-skalyar nazariyasida zaryadlangan qora oʻra atrofida elektr Penrouz jarayonini oʻrganish;

Kalb Ramond gravitatsiyasidagi qora oʻra atrofida Penrouz jarayonini tekshirish;

Regulyar qora oʻra atrofidagi fazo-vaqtning egrilik invariantlari, hodisa gorizonti va magnit maydon xossalarini oʻrganish.

Tadqiqotning obyekti muqobil gravitatsiya nazariyasida zaryadlangan qora o‘ralar va zaryadlangan regulyar qora o‘ralar.

Tadqiqotning predmeti Eynshteyn-Maksvell-skalyar nazariyasi va Kalb Ramond gravitatsiyasidagi elektr Penrouz jarayoni.

Tadqiqotning usullari umumiy nisbiylik elektrodinamik maydonlar uchun matematik apparatlar, nochiziqli va chiziqli differensial tenglamalarni sonli yechish usullari.

Tadqiqotning ilmiy yangiligi quyidagilardan iborat:

ilk bor Eynshteyn-Maksvell-skalyar nazariyasida zararlangan qora o‘ra yaqinida massasiz manfiy skalyar maydon hisobiga zaryadlangan zarrachalarning sinxrotron nurlanishining intensivligi va elektr Penrouz jarayonining samaradorligi oshganligi aniqlandi;

ilk bor qora o‘ra zaryadining bir xil qiymatlari uchun Kalb Ramond gravitatsiyasida Penrouz elektr jarayonining samaradorligi umumiy nisbiylik nazariyasidagi qora o‘ralarga nisbatan yuqori ekanligi ko‘rsatildi;

ilk bor Novikov-Thorn modelida, regulyar qora o‘ra atrofidagi magnitlangan zarralardan iborat bo‘lgan akkretsiya diskidan energiya chiqarish samaradorligi Kerr qora o‘ralaridan (20%) oshib, 22% ga yetganligi hisoblangan;

zarrachalarning magnitlanish parametrining katta qiymatida qora o‘raning akkretsiya diski ichki radiusi chiziqli va chiziqsiz elektrodinamika uchun bir xil ekanligi ko‘rsatilgan.

Tadqiqotning amaliy natijalari

Eynshteyn-Maksvell-skalyar nazariyasida zaryadlangan qora o‘ra atrofida zaryadlangan zarrachalarning sinxrotron nurlanishi tekshirildi va nurlanish intensivligi Reissner-Nordström qora o‘rasi bilan solishtirildi;

zaryadlangan zarrachalarning to‘qnashuvini o‘rganish natijalari olindi va Kalb Ramond gravitatsiyasidagi elektr zaryadlangan qora o‘ra uchun kritik burchak momenti topildi. Qarama-qarshi (qora o‘raning zaryadiga nisbatan) zaryadlangan zarralar Qulon o‘zaro ta’siri tufayli kattaroq kritik burchak momentiga ega ekanligi ko‘rsatilgan;

zarrachalarning magnitlanish parametri regulyar qora o‘ra yaqinidagi zarrachalar harakatiga tasiri o‘rganiladi va real astrofizik tizim uchun uning ekstremumi topiladi.

Tadqiqot natijalarining ishonchliligi quyidagilar bilan ta‘minlanadi:

umumiy nisbiylik nazariyasi va astrofizikaning ilg’or usullari, samarali raqamli usullar va algoritmlar qo‘llaniladi;

boshqa mualliflarning nazariy natijalari izchillik uchun diqqat bilan ko‘rib chiqiladi;

xulosalar ixcham gravitatsion obyektlarning maydon nazariyasining asosiy tamoyillariga juda mos keladi.

Tadqiqot natijalarining ilmiy va amaliy ahamiyati

Eynshteyn-Maksvell-skalyar nazariyasida zaryadlangan qora o‘ra uchun olingan natijalar massasiz skalyar maydon qora o‘radan energiya chiqarish samaradorligiga qanday ta‘sir qilishi haqida ma‘lumot berishi mumkin;

Kalb Ramon gravitatsiyasidagi zaryadlangan qora oʻra atrofidagi elektr Penrouz va zarrachalar toʻqnashuvi jarayoniga Kabl Ramond maydonning taʻsirini oʻrganish muqobil gravitatsiya nazariyasida qora oʻralar fazo vaqti hususiyatlarini oʻrganishda foydali boʻlishi mumkin;

magnitlangan zarrachalar harakatini va ularning magnit zaryadlangan regulyar qora oʻralar atrofidagi energetik jarayonlarini oʻrganish boʻyicha olingan natijalar magnitlangan zarrachalardan tashkil topgan akkretsiya diskini va magnitlangan neutron yulduzlarining galaktika markazi atrofidagi harakat dinamikasini tadqiq qilishda qoʻllash mumkin.

Tadqiqot natijalarining joriy etilishi.

Turli gravitatsiya nazariyalarida zaryadlangan qora oʻralar atrofida zaryadlangan zarralar dinamikasini va energitik jarayonlarning natijalari quyidagi ishlarda qoʻllanilgan:

zaryadlangan regulyar qora oʻra atrofida magnitlangan va magnit zaryadlangan zarralar uchun aylanma orbitalarni aniqlash natijalari bir nechta mualliflar tomonidan qora oʻralar atrofidagi fazo-vaqt xususiyatlarini oʻrganishda foydalanilgan (Physical Review D 108(4), 044030, (2023), European Physical Journal C83(11), 989, (2023), European Physical Journal C 84(2),203, (2024), Physics of the Dark Universe 46,101616, (2024)). Natijalar qora oʻralar uchun nazariy maʻlumotlar asosida qora oʻralar atrofida magnitlangan va magnit zaryadlangan zarrachalarning harakatini tahlil qilish imkonini berish uchun taqdim etildi;

zaryadlangan qora oʻralar atrofidagi energetik jarayonlarini oʻrganish natijalari bir qator mualliflar tomonidan muqobil gravitatsiya nazariyalari uchun foydalanilgan (Physical Review D 108(4), 044030, (2023), European Physical Journal C83(11), 989, (2023), European Physical Journal C 84(2), 203, (2024), Physics of the Dark Universe 46,101616, (2024)). Natijalar zaryadlangan zarrachalarning aylanma orbitalarini va ularning zaryadlangan qora oʻralar energiya xususiyatlarini tahlil qilish uchun ishlatiladi.

Tadqiqot natijalarining approbatsiyasi

Dissertatsiya natijalari 1 ta xalqaro konferensiya (ICTPA-2024), Respublika miqyosida oʻtkazilgan 2 ta ilmiy konferensiyada va nazariy fizika va astrofizika boʻyicha haftalik muntazam oʻzbek-qozoq seminarlarida muhokama qilindi.

Tadqiqot natijalarini nashr etish. Dissertatsiya natijalari 7 ta ilmiy maqoladan iborat boʻlib, 4 tasi xorijiy Web of Science va Scopus bazalaridagi jurnallarida chop etilgan (EPJC Q1, IJMPD Q2).

Dissertatsiyaning hajmi va tuzilishi. Dissertatsiya ishi kirish, 3 ta bob, xulosalar va adabiyotlar roʻyxatidan iborat. Dissertatsiyaning umumiy hajmi 101 sahifa.

DISSERTATSIYANING ASOSIY MAZMUNI

Kirish qismida dissertatsiyaning dolzarbligi, ahamiyati, maqsad va vazifalari, ilmiy va amaliy yangiligi koʻrsatilgan. Olingan natijalarning nazariy va amaliy ahamiyati muhokama qilinadi.

“**Eynshteyn-Maksvell-skalyar nazariyasida zaryadlangan qora oʻralar**

atrofida sinxrotron nurlanishi va Penrouz jarayoni" nomli 1-bobda biz Eynshteyn-Maksvell-skalyar (EMS) nazariyasidagi zaryadlangan qora o'ra yechimlarini qisqacha ko'rib chiqamiz. Harakat quyidagicha beriladi

$$S = \int d^4x\sqrt{-g}\left[R - 2\nabla_\alpha\phi\nabla^\alpha\phi - K(\phi)F_{\alpha\beta}F^{\alpha\beta}\right]$$

bu yerda ∇_α - kovariant hosila, g - $g_{\mu\nu}$ ning aniqlovchisi, R - fazo-vaqt egriligida Richi skalari, ϕ - massasiz skalyar maydon, $F_{\alpha\beta}$ - elektromagnit maydon tenzori, $K(\phi)$ – esa dilaton va elektromagnit maydon o'rtasidagi bog'lanish funksiyasi.

Qora o'ralar uchun umumiy yechim quyidagi shaklda ko'rsatilgan

$$ds^2 = -U(r)dt^2 + \frac{dr^2}{U(r)} + f(r)(d\theta^2 + \sin^2\theta\, d\varphi^2) \tag{1}$$

bu yerda $U(r)$ va $f(r)$lar $K(\phi)$ funksiyasi uchun maxsus shakllarga ega radial funksiyalardir

$$K(\phi) = \frac{2e^{2\phi}}{\beta e^{4\phi} + \beta - 2\gamma}\,, \tag{2}$$

va yechimlarni quyidagi ko'rinishda oldik

$$f(r) = r^2\left(1 + \frac{\gamma Q^2}{Mr}\right),$$

$$U(r) = 1 - \frac{2M}{r} + \frac{\beta Q^2}{f(r)}. \tag{3}$$

va M - umumiy massa hamda Q - elektr zaryad. $\beta = 0$ va $\gamma = 0$ bo'lganida Schwarzschild yechimiga keladi, $\gamma = 0$ va $\beta = 1$ holatda Reissner-Nordström (RN) BH.

Shuni ta'kidlash lozimki, vektor va dilaton maydonlari radial koordinataga faqat quyidagicha bog'liq deb taxmin qilingan

$$A_t(r) = \frac{Q}{r}\left[\gamma - \frac{\beta}{2}\left(1 + \frac{r^2}{f(r)}\right)\right]. \tag{4}$$

Biz EMS nazariyasida zaryadlangan qora o'ralar atrofida elektromagnit kuchlar (Kulon va Lorents kuchlari) tufayli tezlashtirilgan zaryadlangan zarrachalardan chiqadigan sinxrotron nurlanishini tekshiramiz. EMS qora o'rasi atrofida aylanayotgan zaryadlangan zarralar o'zidan sinxrotron nurlanishlar ishlab chiqaradi. Bu esa o'z navbatida zarrachalarni relativistik tezlikgacha tezlanishi evaziga yuzaga keladi. EMS qora o'rasining fazoda orbital harakati bilan zaryadlangan zarrachaning sinxrotron nurlanishini tekshirish uchun biz quyidagi ifodadan foydalanamiz

$$I = \frac{2q^2}{3}\omega_\alpha\omega^\alpha, \tag{5}$$

bu yerda ω_α - qora o'ra atrofida aylanib yuruvchi zaryadlangan zarrachalarning tezlanishi to'gridan to'g'ri kuzatuvchi tomonidan o'lchanadi:

$$\omega^\alpha = \frac{q}{m}F^\alpha_\beta u^\beta, \qquad \omega_\alpha u^\alpha = 0. \tag{6}$$

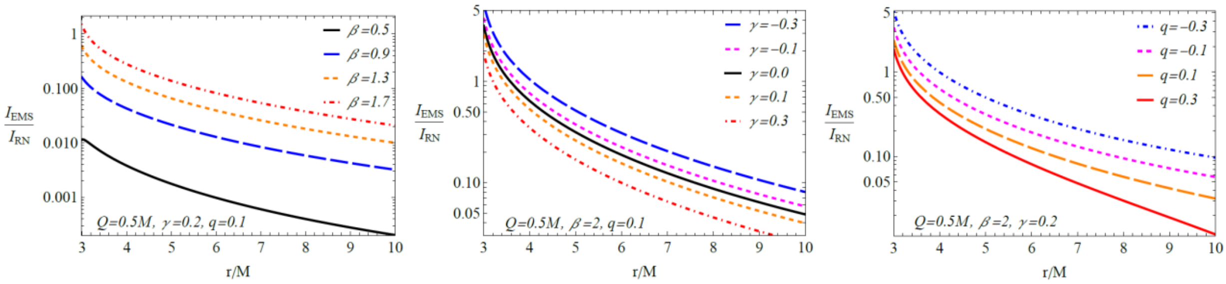
(6) - tenglamaning ikkinchi qismi zarracha tezligi uning tezlanishiga perpendikulyar ekanligini bildiradi. Tezlik komponentlari bilan barqaror aylana orbita bo'ylab harakatlanadigan zaryadlangan zarracha: $u^\alpha = u^t(1,0,0,\Omega)$, tezlanish esa $\omega^\alpha = (0, \omega^r, \omega^\theta, 0)$ ko'rinishga ega. Zarrachaning tezlanish vektorining nolga teng bo'lmagan komponentlari:

$$\omega_r = \frac{q\Omega F_{rt}}{m\sqrt{-g_{tt}-\Omega^2 g_{\phi\phi}}}, \qquad \omega_\theta = 0. \tag{7}$$

Nurlanishning intensivligini (6) - tenglama yordamida quyidagi shaklda oson hisoblash mumkin:

$$I = -\frac{2q^4}{3m^2}\frac{g^{rr}F_{rt}^2}{g_{tt}+\Omega^2 g_{\phi\phi}}. \tag{8}$$

1-rasmda zaryadlangan zarrachalarning sinxrotron nurlanish intensivliklarining nisbati (I_{EMS}/I_{RN}) ko‘rsatilgan. Rasmda (chap tomondagi grafik) nurlanish intensivligi β parametrining qiymatlari oshishi bilan ortib borishini ko‘rsatadi. Sinxrotron nurlanishi intensivligining skalyar maydonga (zarrachalar zaryadi q) bog’liqligi o‘rganildi (o‘rtadagi va o‘ng tomondagi grafiklar). Intensivlik γ (q) ning musbat qiymatlari bilan kamayadi va manfiy qiymatlar bilan ortadi.



1-rasm. I_{EMS}/I_{RN} intensivliklari nisbati EMS parametrlarining turli qiymatlari va zarrachalarning zaryadi uchun radial koordinatalar funksiyasi sifatida tahlil qilingan.

Endi biz $\Omega = d\pi/dt$ cheksizlikda joylashgan statik uzoq kuzatuvchi tomonidan o‘lchangan parchalangan zarrachalarning burchak tezligi uchun quyidagi tenglamani olamiz

$$\Omega = \pm\frac{1}{u^t\sqrt{f(r)}}\sqrt{(u^t)^2\left[U(r) - \frac{v^2}{U(r)}\right] - k}\,. \tag{9}$$

Ω ning mavjud qiymatlari quyidagilar bilan cheklangan:

$$\Omega_- \leq \Omega \leq \Omega_+, \quad \Omega_\pm = \pm\sqrt{\frac{U(r)}{f(r)}}\,. \tag{10}$$

va Kepler orbitalariga mos keladi.

Biz zaryadlangan zarracha (1) EMS nazariyasidagi zaryadlangan qora o‘raga cheksizlikdan yaqinlashib, ekvator tekisligidagi hodisa gorizonti yaqinida ikkita zaryadlangan qismga (2 va 3) parchalanishi holatini ko‘rib chiqamiz. Biz parchalanish jarayoni energiya, impuls va zaryadning saqlanish qonunlarini qondiradi deb faraz qilamiz

$$E_1 = E_2 + E_3, \;\; L_1 = L_2 + L_3, \;\; q_1 = q_2 + q_3, \tag{11}$$

$$m_1\dot{r}_1 = m_2\dot{r}_2 + m_3\dot{r}_3, m_1 \geq m_2 + m_3, \tag{12}$$

bu yerda ifoda yuqorisida joylashgan nuqtalar tegishli vaqt bo‘yicha hosilalarni anglatadi. (11) va (12) tenglamalardan foydalanib, quyidagi tenglamani topishimiz mumkin

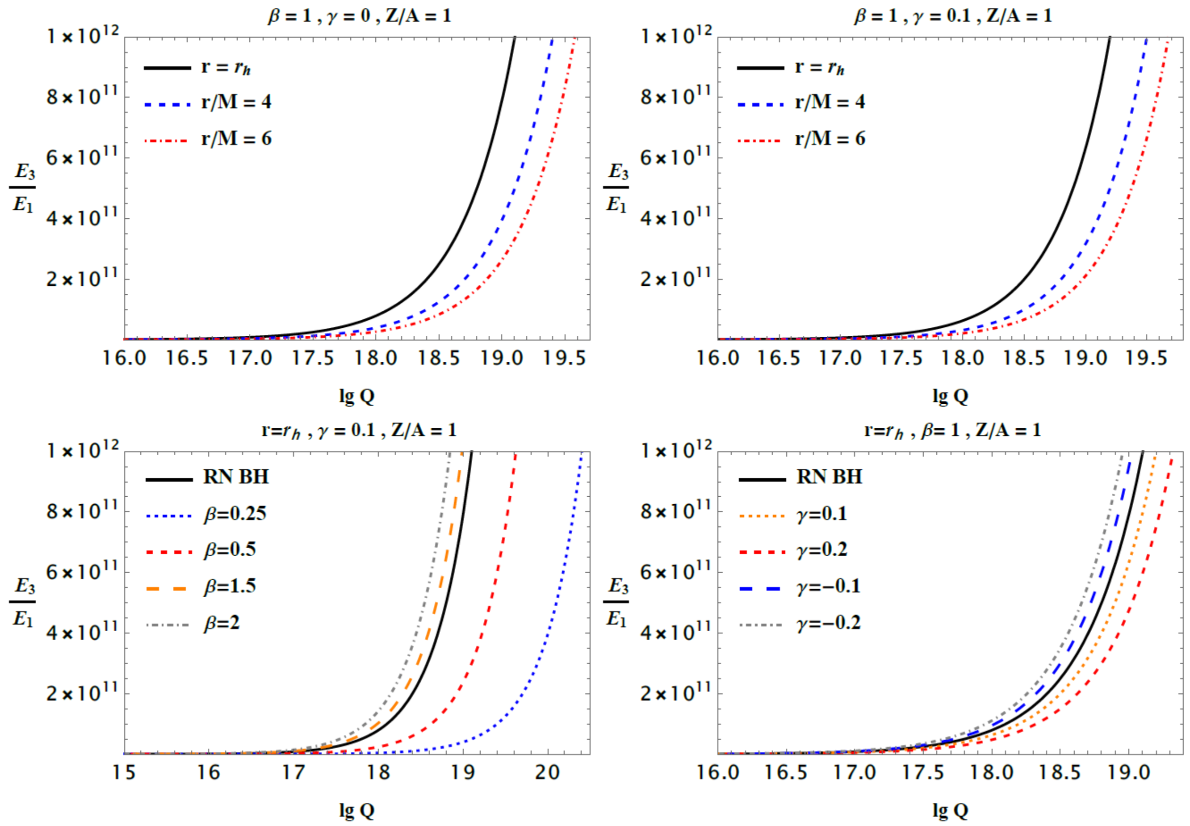
$$m_1 u_1^\phi = m_2 u_2^\phi + m_3 u_3^\phi, \tag{13}$$

bu yerda $u^{\phi} = \Omega u^t = \Omega e/f(r)$, $e_i = (E_i + q_i A_t)/m_i$, va i = 1,2,3 zarracha sonini ko‘rsatadi. (13) tenglamani quyidagi ko‘rinishga keltirish mumkin

$$\Omega_1 m_1 e_1 = \Omega_2 m_2 e_2 + \Omega_3 m_3 e_3. \quad (14)$$

bu yerda $\Omega_i = d\phi_i/dt$ - (9) tomonidan berilgan i inchi zarrachaning burchak tezligi, (10) esa cheklangan qiymatlar. (14) - tenglamani yechish orqali biz zarralardan birining energiyasini topishimiz mumkin, masalan, E_3:

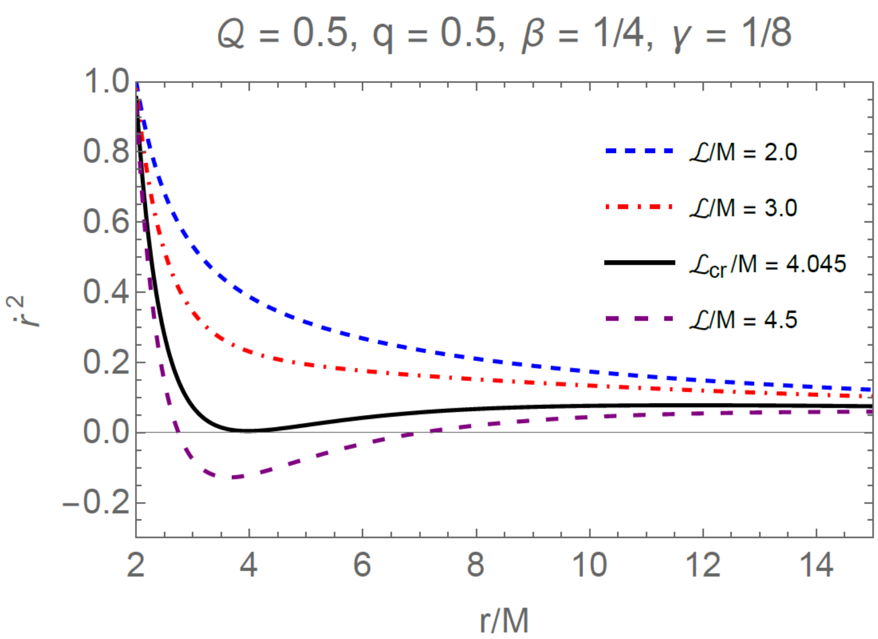
$$E_3 = \frac{\Omega_1 - \Omega_2}{\Omega_3 - \Omega_2}(E_1 + q_1 A_t) - q_3 A_t. \quad (15)$$



2-rasm. Fazo-vaqt parametrlarining turli qiymatlari uchun qora o‘ra zaryadi Q ga nisbatan chizilgan ionlangan va neytral zarrachalar energiyalarining nisbati. Pastki panellaridagi qora uzliksiz chiziq RN qora o‘rasining, $\beta = 1$ va $\gamma = 0$ holatiga mos keladi.

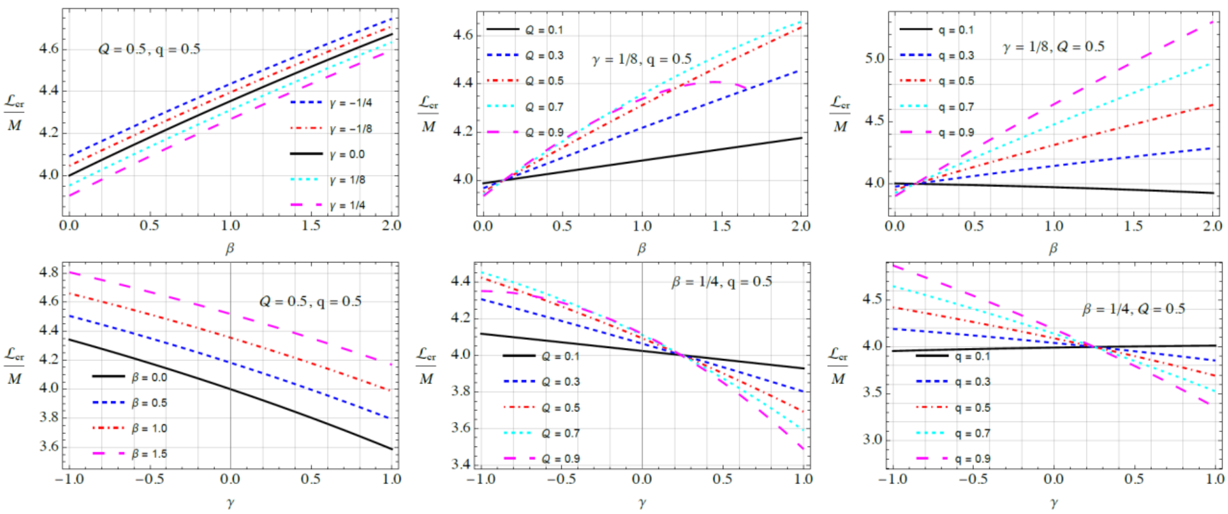
2-rasmda EMS parametrlari E_3/E_1 ga bog’liqligini grafik tahlillar orqali taqdim etamiz. 2-rasmda tezlanish mexanizmi samaradorligi ($Z/A = 1$ bo‘lgan ionlangan va neytral zarracha nisbati) qora o‘ra zaryadiga bog’liqligi chizilgan. Tezlanish mexanizmining samaradorligi qora o‘raning zaryadlanishi bilan ortadi va qora o‘ra va ionlanish nuqtasi orasidagi masofa oshgani sayin biroz pasayadi (2-rasmning yuqori panelida ko‘rsatilganidek). Bundan tashqari, qora o‘ra zaryadining ma'lum bir qiymatiga mos keladigan samaradorlik β parametriga to‘g’ri proportsional va γ parametriga teskari proportsionaldir(2-rasmning pastki panelida ko‘rsatilganidek).

Burchak momentining kritik qiymatini ikkita shart bilan aniqlash mumkin: (a) $\dot{r} = 0$ va (b) $d\dot{r}/dr = 0$. Bu 3-rasmda ko‘rsatilgan. Burchak momentining ortishi radial tezlik kvadratining manfiy bo'lishiga olib keladi, bu esa zarralar endi markaziy obyektga shu qiymatdan yaqinlasha olmasligini bildiradi. Shuning uchun biz burchak momentining mavjud qiymatlarini o'rganib chiqdik va kritik qiymatlarni aniqladik.



3-rasm. Zarrachaning burchak momentining turli qiymatlari uchun radial tezlik kvadratining radial bog'liqligi.

4-rasmda qora o'ra parametrlari va zarracha zaryadining turli qiymatlari uchun kritik burchak momentining EMS parametrlariga bog'liqligi ko'rsatilgan. Yuqori uchta panel γ parametrining turli qiymatlari uchun magnit parametr (β) funksiyasi sifatida kritik burchak momentini ko'rsatadi. Chap panel γ ni oshish burchak momentining ruxsat etilgan qiymatini kamaytirishini va β parametr bilan chiziqli bog'liqlik mavjudligini ko'rsatadi. O'rtada joylashgan panel qora o'ra zaryadining kattaroq qiymatlari uchun chiziqlilik buzilganligini ko'rsatadi.



4-rasm. Qora o'ra va zarracha parametrlarining turli qiymatlari uchun kritik burchak momentining β (yuqori panellar) va γ (pastki panellar) ga bog'liqligi.

O‘ng panelda zarracha zaryadini o‘zgartirish ta'siri tasvirlangan. Pastki panellar γ ning funksiyasi sifatida burchak momentini ko‘rsatadi. Aksariyat hollarda burchak impulsi γ ga chiziqli bog’liq bo‘lib, γ ning ortishi β parametrli xatti-harakatlarga qarama-qarshi bo‘lib, burchak momentining pasayishiga olib keladi. O‘rta va o‘ng panellar mos ravishda qora o‘ra va zarrachalar zaryadini o‘zgartirish orqali yuqori panelning harakatini takrorlaydi. Pastki chap rasmda qora o‘raning magnit parametri βni o‘zgartirish orqali chizib ko‘rsatilgan.

“Kalb-Ramond gravitatsiyasida zaryadlangan qora o‘ralar atrofida Elektr Penrouz va zaryadlangan zarrachalarning to‘qnashuvi” deb nomlangan ikkinchi bobda biz elektr zaryadlangan zarrachalarning statik zaryadlangan qora o‘ra atrofida harakatlanish tenglamasini keltirib chiqarishga qaratilgan. Sferik simmetrik fazo-vaqt geometriyasiga ega zaryadlangan qora o‘ra sferik koordinatalarni ($x^{\alpha} = \{t, r, \theta, \phi\}$) quyidagi shaklda ko‘rsatiladi,

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\,, \tag{16}$$

bu yerda $f(r)$ - radial funksiyasi quyidagicha berilgan:

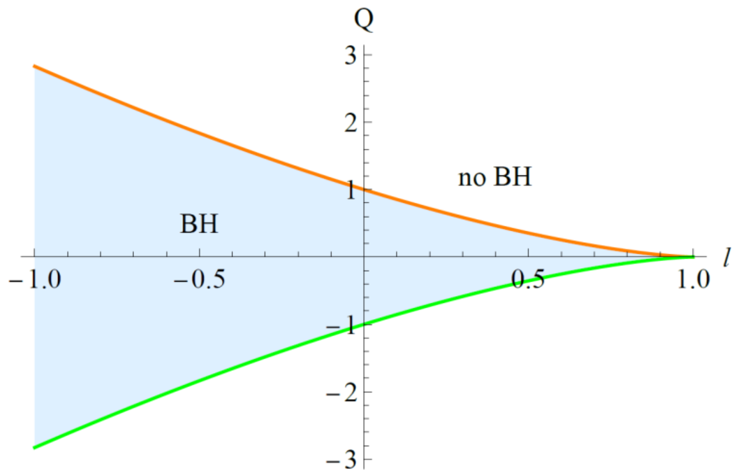
$$f(r) = \frac{1}{1-l} - \frac{2M}{r} + \frac{Q^2}{r^2(1-l)^2}\ . \tag{17}$$

Bu yerda M qora o‘raning umumiy massasini, Q esa uning elektr zaryadini ifodalaydi. Quyosh tizimida o‘tkazilgan klassik tortishish o‘lchovlari shuni ko‘rsatdiki, Kalb-Ramond (KR) maydonining nolga teng bo‘lmagan vakuum kutilgan qiymati tomonidan yaratilgan Lorentsni buzuvchi ta'sirni ifodalovchi o‘lchamsiz parametr l juda kichik qiymatga ega bo‘lishi kerak. $l = 0$ bo‘lganda, u standart RNga o‘xshagan metrikaga yaqinlashadi.

5-rasmda biz ekstremal qora o‘ra zaryadi va KR parametri o‘rtasidagi munosabatlar ko‘rsatilgan. Och-ko‘k soyali maydon Q va l qiymatini nazarda tutadi, bunda fazo-vaqt (17) o‘raga tegishli hodisa gorizontiga ega. Q va l ning soyasi maydondan tashqaridagi qiymatlarida qora o‘ra hodisa gorizontisiz obyektga aylanadi.

Shuni ham ta'kidlash joizki, vektor va dilaton maydonlari faqat radial koordinataga quyidagi shaklda bog’liq deb taxmin qilingan:

$$A_t(r) = \frac{Q}{(1-l)r}. \tag{18}$$



5-rasm. Qora o‘ra zaryadining Q ekstremal qiymatlarining l ga bog’liqligi.

Biz cheksiz masofada joylashgan statik kuzatuvchi ko‘radigan parchalangan zarrachalarning burchak tezligini tavsiflovchi ifodani keltirib chiqaramiz. Buning uchun bizda

$$\zeta = \pm\frac{1}{v^t r}\sqrt{(v^t)^2\left[f(r) - \frac{\mu^2}{f(r)}\right] - \lambda}\,. \tag{19}$$

ζ uchun potentsial qiymatlar diapazoni quyidagicha cheklangan:

$$\zeta_- \leq \zeta \leq \zeta_+, \qquad \zeta_\pm = \pm\sqrt{\frac{f(r)}{r^2}}\,, \tag{20}$$

bu Kepler orbitalariga mos keladi.

Keyinchalik, Kalb-Ramond gravitatsiyasi nazariyasida zaryadlangan zarracha zaryadlangan qora o‘raga cheksizlikdan yaqinlashib, hodisa gorizonti yaqinida ekvator tekisligida ikkita zaryadlangan zarrachaga parchalanishi holatini ko‘rib chiqamiz. Biz energiya, impuls va zaryadning saqlanish qonunlari parchalanish jarayonini qondiradi deb hisoblaymiz (10-11).

Yuqoridagi tenglamalardan foydalangan holda

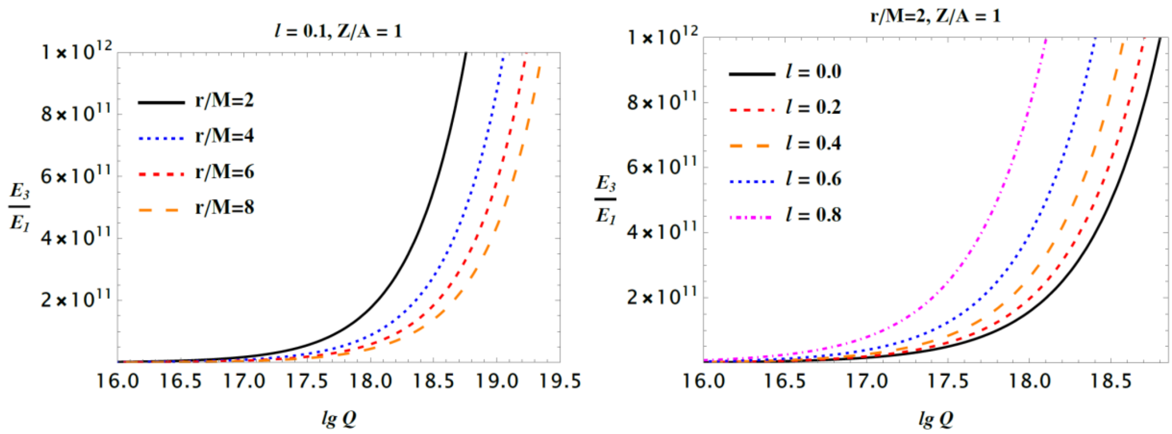
$$m_1 v_1^\phi = m_2 v_2^\phi + m_3 v_3^\phi, \tag{21}$$

bu yerda $v^\phi = \zeta v^t = \zeta e/r^2$, $e_i = (E_i + q_i A_t)/m_i$ va $i = 1,2,3$ zarrachalar sonini bildiradi. Endilikda (21) tenglamani quyidagicha ifodalash mumkin:

$$\zeta_1 m_1 e_1 = \zeta_2 m_2 e_2 + \zeta_3 m_3 e_3. \tag{22}$$

i -zarrachaning burchak tezligi $\zeta_i = d\phi_i/dt$ bilan belgilanadi, (19) tenglama bilan aniqlanadi va (20) tenglamada ko‘rsatilgan cheklovlarga bo‘ysunadi. E_3 kabi zarracha energiyasini (22) tenglamani yechish orqali aniqlash mumkin. Bizda

$$E_3 = \frac{\zeta_1 - \zeta_2}{\zeta_3 - \zeta_2}(E_1 + q_1 A_t) - q_3 A_t. \tag{23}$$



6-rasm. Fazo-vaqt parametrlarining turli qiymatlari uchun qora o‘ra zaryadi Q ga nisbatan chizilgan energiyalar nisbati. $l = 0$ standart RN qora o‘ra yechimlari(o‘ng panel) natijalarini ko‘rsatadi.

Biz elektromagnit to‘rtta potensial va metrik funksiyalarning vaqt komponenti bo‘yicha qora o‘ra massasi va yorug’lik tezligini to‘g’ridan-to‘g’ri ifodalash orqali E_3/E_1 uchun yakuniy tenglamani keltirib chiqarishimiz mumkin. Bu tenglama murakkab bo‘lib, uni yechish qiyindir. Lekin biz uning qora o‘ra parametrlariga bog’liqligini 6-rasmda vizual tarzda tasvirlaymiz. 6-rasmda (chap panelda) $Z/A = 1$

bo‘lgan ionlangan va tushuvchi zarrachalar energiyalarining nisbati bo‘lgan tezlanish mexanizmining samaradorligi ko‘rsatilgan. Rasmda quyosh massasiga to‘g’ri keladigan qora o‘ra zaryadining funksiyasi sifatida turli ionlanish joylarida ushbu samaradorlik ko‘rsatilgan. Qora o‘ra zaryadi oshishi bilan samaradorlik sezilarli darajada oshadi. Bundan tashqari, qora o‘ra va ionlanish nuqtasi orasidagi masofa oshgani sayin u kamayadi. Parametr l (o‘ng panel) o‘zgartirilganda, ushbu parametrning oshishi bilan samaradorlik ortadi.

Massa markazi energiyasining umumiy ifodasi quyidagicha ifodalanishi mumkin

$$\{E_c, 0,0,0\} = m_1 u_1^{\mu} + m_2 u_2^{\mu}, \tag{24}$$

u_1^{α} va u_2^{β} o‘zgaruvchilari to‘qnashuvda ishtirok etgan ikkita zarrachaning to‘rtta tezligini ifodalaydi, m_1 va m_2 mos massalari. (24) tenglamada ko‘rsatilganidek, massa markazining energiyasi kvadratini hisoblash va natijasini olish oson.

$$E_c^2 = m_1^2 + m_2^2 - 2m_1 m_2 g_{\mu\nu} u^{\mu} u^{\nu}, \tag{25}$$

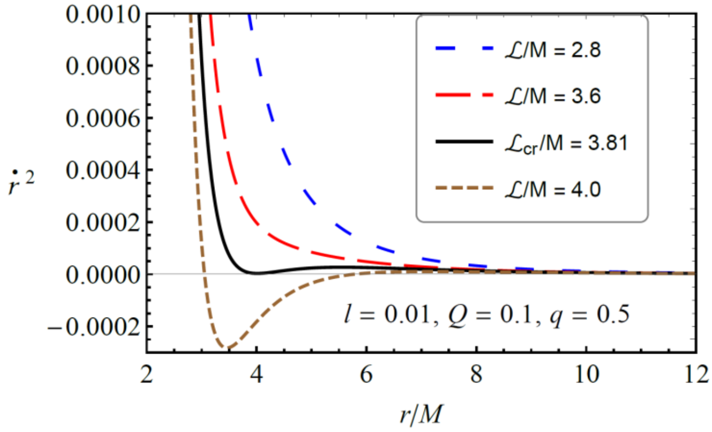
$$\frac{E_c^2}{m_1 m_2} = \frac{m_1}{m_2} + \frac{m_2}{m_1} - 2g_{\mu\nu} u_1^{\mu} u_2^{\nu}. \tag{26}$$

To‘qnashuvchi zarrachalarning massalari $m_1 = Am$ va $m_2 = Bm$ deb belgilangan holatda bizda

$$\frac{E_{cm}^2}{m^2 c^4} = A^2 + B^2 - 2g_{\mu\nu} u_1^{\mu} u_2^{\nu}. \tag{27}$$

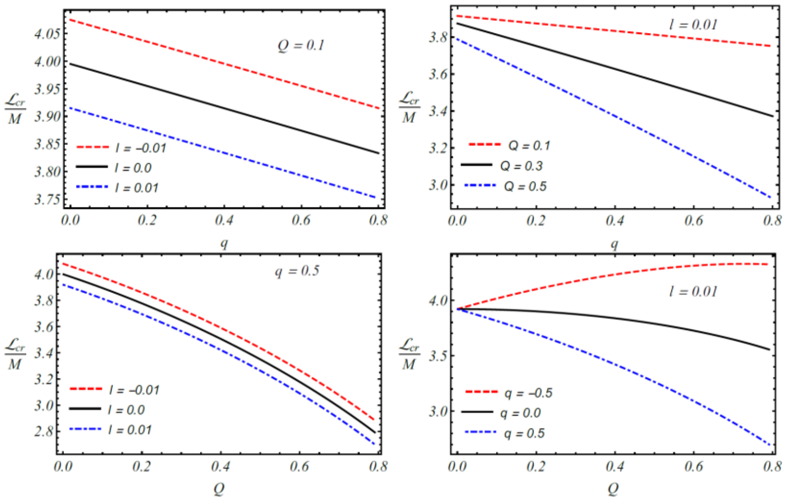
Keyin bir xil boshlang’ich energiya va massaga ega bo‘lgan zarrachalarning to‘qnashuvini tekshiramiz $(E_1 = E_2 = m)$. Kalb-Ramond qora o‘ra yaqinidagi zaryadlangan zarrachalarning tezlanishini teng massali ikkita to‘qnashuvchi zarrachaning massa energiyasi markazi uchun standart tenglamani qo‘llash orqali tekshiramiz. Natijada, massa markazi energiyasi uchun tenglama hosil bo‘ladi.

$$\varepsilon_c^2 = \frac{E_c^2}{4m^2 c^4} = 1 - g_{\alpha\beta} u_1^{\alpha} u_2^{\beta}. \tag{28}$$



7-rasm. Zarrachaning burchak momentining turli qiymatlari uchun radial tezlik kvadratining radial bog’liqligi.

Ikkita shart: (i) $\dot{r} = 0$ va (ii) $d\dot{r}/dr = 0$ burchak momentining kritik qiymatini aniqlashga imkon beradi. 7-rasm buni ko‘rsatadi. Manfiy radial tezlik burchak momentining oshishi natijasida yuzaga keladi. Ushbu qiymatdan zarralar markaziy obyektga yaqinlasha olmaydi. Shunday qilib, kritik qiymatlarni aniqlash uchun burchak momentining mavjud qiymatlarini ko‘rib chiqdik. Qora o‘ra parametrlari va zarrachalar zaryadining turli qiymatlariga kritik burchak momentining bog’liqligi 8-rasmda ko‘rsatilgan. Yuqori panellar kritik burchak momenti va parametr (q) o‘rtasidagi bog’liqligini l(chap tomonda) va Q (o‘ng tomonda) parametrlarining turli qiymatlari bo‘yicha ko‘rsatadi. Yuqori chap panelda l qiymati ortishi bilan burchak momentining ruxsat etilgan diapazoni pasayib borishi va q parametri bilan chiziqli munosabat mavjudligini ko‘rsatadi. Xuddi shunday, pastki panelda l(chapda) va q (o‘ngda) turli parametrlarni hisobga olgan holda, qora o‘ra zaryadi Q bilan kritik burchak momentini tasvirlaydi. Shunga o‘xshash xatti-harakatlar ikkala holatda ham kuzatilishi mumkin.



8-rasm. Qora o‘ra va zarracha parametrlarining turli qiymatlari uchun kritik burchak momentining q (yuqori panellar) va Q (pastki panellar) ga bog’liqligi.

“Magnit zaryadlangan regulyar qora o‘ra muhitidagi zarrachalar dinamikasi” deb nomlangan uchinchi bobda umumiy gravitatsiya nazariyasida (GR) regulyar qora o‘ralar (RBH) yechimini olish uchun uni quyidagi shakldagi harakat yordamida nochiziqli elektrodinamika (NED) bilan birlashtirish kerak.

$$S = \frac{1}{16\pi}\int dx^4\sqrt{-g}\big(R - L(F)\big) \tag{29}$$

bu yerda $F = F^{\mu\nu}F_{\mu\nu}$ elektromagnit maydon potentsiali A_μ bilan ifodalangan $F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$ elektromagnit maydon tenzori yordamida tuzilgan elektromagnit maydon invariantidir.

Lagrangianning quyidagi shakli yordamida regulyar qora o‘ra yechimini olish mumkin

$$L(F) = 4Fe^{-\left(\frac{q}{\sqrt{2}}\right)^{\frac{3}{2}}\frac{F^{\frac{1}{4}}}{M}}, \tag{30}$$

Regulyar qora o‘ra yechimini olish uchun biz $F = q^2/(2r^4)$ va NED maydonining mos keladigan Lagranjianini quyidagi shaklda ishlatdik.

$$L(F) = \frac{2q^2}{r^4}e^{-\frac{q^2}{2Mr}}, \tag{31}$$

bu yerda q magnit zaryad. Bunday regulyar qora o‘ra atrofida sferik simmetrik fazo-vaqt uchun metrik tensor quyidagicha ifodalanishi mumkin:

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

shaklning uzilish funksiyasi

$$f(r) = 1 - \frac{2M}{r} e^{-\frac{q^2}{2Mr}}, \tag{32}$$

bu erda M – regulyar qora o‘raning umumiy massasi. $q = 0$ bo‘lgandagi yechim Shvartshild vakuum yechimiga aylanadi.

Shundan so‘ng, biz magnitlangan zarrachalar dinamikasini magnit zaryadlangan muntazam qora o‘ralar atrofida Gamilton-Yakobi tenglamasidan keyin uzilish funksiyasi (32) bilan tasvirlanganda o‘rganamiz. Elektromagnit to‘rt potentsial shaklga ega

$$A_\phi = q\cos\theta. \tag{33}$$

(33) dagi potensialdan foydalanib, elektromagnit maydon tenzorining nolga teng bo‘lmagan komponentini olish mumkin.

$$F_{\theta\phi} = -q\sin\theta\ . \tag{34}$$

Muntazam qora o‘raning magnit zaryadidan hosil bo‘lgan magnit maydonning ortonormal radial komponenti quyidagicha yozilishi mumkin:

$$B^{\hat{r}} = \frac{q}{r^2}\ , \tag{35}$$

Nyuton shakliga o‘xshash shaklga ega.

Magnit zaryadlangan muntazam qora o‘ra atrofida magnitlangan zarrachaning dinamikasi uchun zarrachaning magnit dipol momentining yo‘nalishi ekvator tekisligiga, shuningdek qora o‘raning magnit maydoniga parallel deb faraz qilamiz. Bu taxmin magnit dipol momenti faqat $\mu^i = (\mu^r, 0{,}0)$ radial komponentlarga ega ekanligini bildiradi. Magnit dipol momentining tarkibiy qismlarining boshqa konfiguratsiyasi magnit shovqinlarning maksimal energiyasi bilan magnit o‘zaro ta'sirda muvozanatni ta'minlay olmaydi. Bu yerda biz magnitlangan zarrachaning harakatiga mos keladigan kuzatuvchi tizimni ko‘rib chiqamiz. Ma'lumotnomaning bunday tanlanishi nisbiy harakatdan kelib chiqadigan muammolarni oldini olishga yordam beradi. Bundan tashqari, biz magnit momentning kattaligi uning aylanma harakati davomida o‘zgarmasligini ko‘rib chiqamiz.

Oldingi ishlarimizda biz magnitlangan qora o‘ra senariylari atrofida magnitlangan zarrachalar harakatida o‘zaro ta'sir atamasi bir xil ekanligini va shaklga ega ekanligini ko‘rsatdik.

$$\mathcal{D}^{\alpha\beta}F_{\alpha\beta} = \frac{2\mu q}{r^2}\ , \tag{36}$$

bu yerda $\mathcal{D}^{\alpha\beta} = \eta^{\alpha\beta\gamma\rho}\mu_\gamma u_\rho$ - qutblanish tenzori, μ_γ va u_ρ- magnitlangan zarrachalarning to‘rt magnitli dipol momenti va tezligi. $\mathcal{D}^{\alpha\beta}F_{\alpha\beta}$ qismi magnitlangan zarrachaning magnit maydonlari va regulyar qora o‘ralar o‘rtasidagi o‘zaro ta'sirni tavsiflaydi. Magnit zaryadlangan qora o‘ralar tomonidan yaratilgan magnit maydon aksial simmetrik harakatga ega va fazo-vaqt simmetriyasini buzmaydi, bu ikki kattalikni: energiya va burchak momentini saqlashga imkon beradi.

Biz magnitlangan zarrachaning ekvator tekisligida radial harakatini tekshiramiz. Bu yerda $\theta = \pi/2, p_\theta = 0$ magnit zaryadlangan, muntazam qora o‘ra atrofida. Radial harakat tenglamasi quyidagi shaklga ega

$$\dot{r}^2 = \mathcal{E}^2 - V_{\rm eff}(r; \mathcal{L}, b, q)\,, \tag{37}$$

effektiv potensial quyidagi shaklga ega

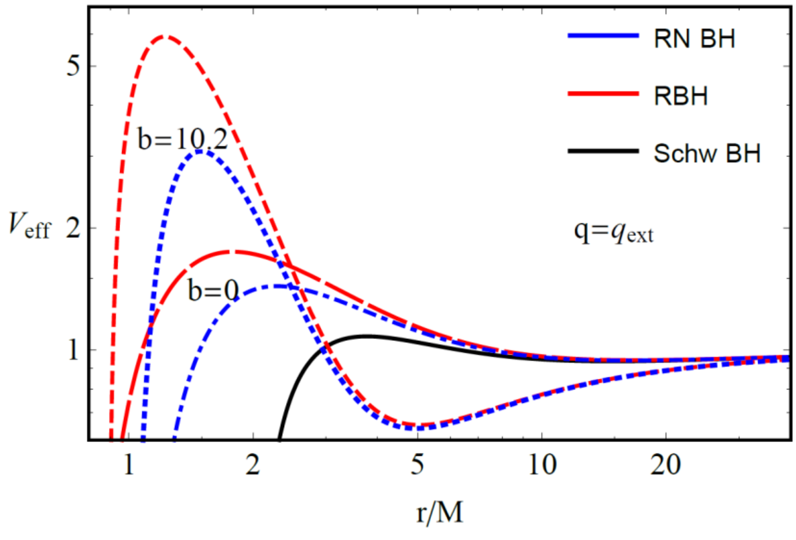
$$V_{eff}(r, \mathcal{L}, \mathcal{B}, q) = \left(1 - \frac{2M}{r} e^{-\frac{q^2}{2Mr}}\right)\left[\left(1 - \frac{\mathcal{B}}{r^2}\right)^2 + \frac{\mathcal{L}^2}{r^2}\right], \tag{38}$$

mos ravishda magnitlangan zarracha va markaziy qora o‘raning parametrlarini tavsiflash uchun magnitlangan zarralar va magnit zaryadlangan muntazam qora o‘ra o‘rtasidagi o‘zaro ta'sir uchun javob beradigan yangi kiritilgan $\mathcal{B} = \mu q/m$ and $b = \mu/(mM)$ parametrlari bilan. Bu yerda biz haqiqiy astrofizik tizimni o‘rganamiz: magnitlangan neytron yulduz o‘ta massiv qora o‘ra atrofida aylanadigan sinov magnitlangan zarracha

$$b = \frac{B_{NS}R_{NS}^3}{2m_{NS}M_{SMBH}} \approx 0.18\left(\frac{B_{NS}}{10^{12}G}\right)\left(\frac{R_{NS}}{10^6 cm}\right)\left(\frac{m_{NS}}{M_\odot}\right)^{-1}\left(\frac{M_{SMBH}}{10^6 M_\odot}\right)^{-1} \tag{39}$$

Ana shunday astrofizik tizimlardan biri SMBH Sgr A* ($M \simeq 3.8 \times 10^6 M_\odot$) orbitasida aylanib yuruvchi magnit SGR (PSR) J1745−2900 ($\mu \simeq 1.6 \times 10^{32} G \cdot cm^3$ va massasi $m \approx 1.5 M_\odot$) hisoblanad va parametr uchun taxminiy qiymat $b \approx 10.2$ holati uchun β.

9-rasmda Shvartshild qora o‘ra holatidagi natijalarni solishtirish bilan magnitlangan zarrachalarning haddan tashqari zaryadlangan muntazam qora o‘ra va RN qora o‘ra atrofida radial harakatining samarali potensialining radial bog’liqligi ko‘rsatilgan. Bu chizmalarda burchak impulsi uchun $\mathcal{L} = 4.3M$ va magnitlangan zarracha uchun $b = 10.2$ dan foydalandik. 9-rasmdan ko‘rish mumkinki, qora o‘raning magnit zaryadining mavjudligi va magnit o‘zaro ta'siri maksimal samarali potensialning oshishiga olib keladi va u ekstremal muntazam qora o‘rada RN ga nisbatan kattaroqdir. Shu bilan birga, samarali potensial markaziy qora o‘ra tomon siljiydigan masofa.



9-rasm. O‘ta zaryadlangan muntazam va RN qora o‘ra atrofida o‘ziga xos burchak momenti $\mathcal{L} = 4.3M$ bo‘lgan magnitlangan $b = 10.2$ (chiziqli chiziqlarda) va neytral (katta chiziqli chiziqlarda) zarrachalarning radial harakatining samarali potensialining radial profillari Shvartshild holati bilan taqqoslash uchun.

Magnitlangan zarrachaning aylana orbitalari bo‘ylab o‘ziga xos burchak momentini ifodalash mumkin

$$\mathcal{L}^2 = \left(1 - b\,\frac{qM}{r^2}\right)\left[2bqM - \frac{(q^2-2Mr)(bMq+r^2)}{2r^2\left(e^{\frac{q^2}{2Mr}}-\frac{3M}{r}\right)+q^2}\right], \tag{40}$$

va energiya uchun

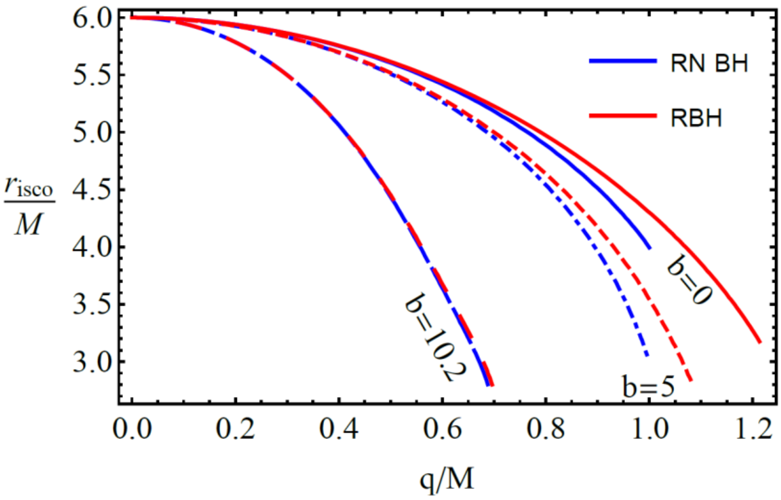
$$\mathcal{E}^2 = \frac{2\left(e^{\frac{q^2}{2Mr}}-\frac{2M}{r}\right)^2 (r^4-b^2M^2q^2)}{r^3\left(e^{\frac{q^2}{2Mr}}(q^2-6Mr)+2r^2 e^{\frac{q^2}{Mr}}\right)}\,. \tag{41}$$

10-rasmda magnitlangan zarrachalarning ISCO radiusining regulyar qora o‘raning magnit zaryadiga bog’liqligi RN qora o‘radagi natijalarni taqqoslash bilan ko‘rsatilgan. Magnit ulanish parametri kichik bo‘lsa, RN qora o‘ra va regulyar qora o‘raning farqini ko‘rish mumkin. Biroq, ulanish parametrining o‘sishi bilan farq magnitlangan zarracha va qora o‘ra magnit maydoni o‘rtasidagi o‘zaro ta'sirning to‘yinganligi sababli yo‘qoladi.

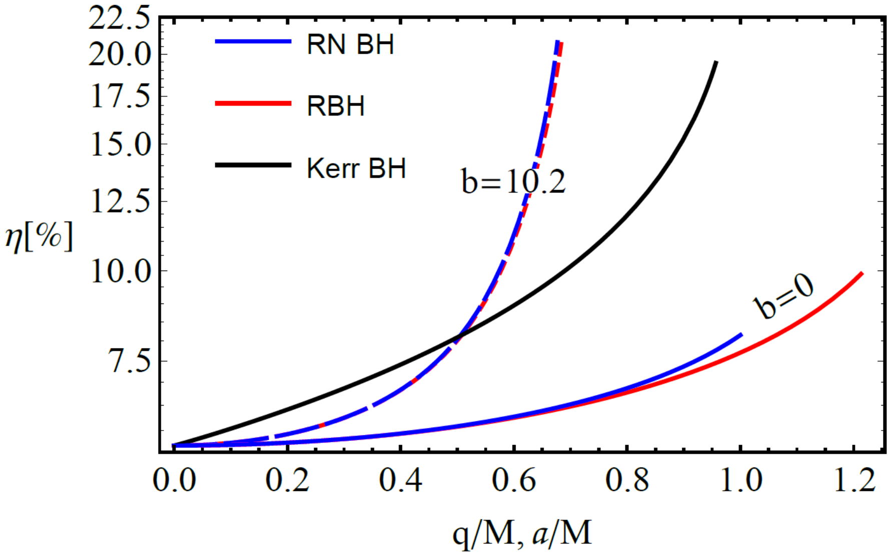
Ma’lumki, Novikov-Thorn modeli astrofizik qora o‘ra atrofida to‘planish diskida to‘plangan moddalarning Kepler orbitalarining mavjudligini tushuntirishga imkon beradi, bu geometrik nozik disklar sifatida yaxshi modellangan aylana geodezik fazoviy vaqtning kuzatish xususiyatlari bilan belgilanadi. Akkretsiya diskidagi elektromagnit nurlanish qora o‘ra atrofidagi akkretsiya diskidan energiya chiqarish samaradorligini tavsiflaydi. Bu diskdan markaziy qora o‘raga tushgan materiyaning nurlanishi orqali yig’ilish diskidan qancha maksimal energiya olish mumkinligini anglatadi. Zarrachalar samaradorligini quyidagi standart ifoda yordamida hisoblash mumkin:

$$\eta = 1 - \mathcal{E}_{\text{ISCO}}, \tag{42}$$

bu yerda $\mathcal{E}_{\text{ISCO}}$ - ISCOdagi zarrachaning energiyasi bo‘lib, u bog’lanish energiyasi (qora o‘ra-zarrachalar tizimi) nisbati bilan tavsiflanadi va sinov zarrachasining dam olish energiyasi tenglamalarda keltirilgan zarrachalarning energiyasidan foydalanib hisoblanishi mumkin (40) va (41) ISCO da. Muntazam qora o‘ra magnit zaryadining samaradorlikka ta'siri 11-rasmda RN va Kerr qora o‘ralardan energiya samaradorligi bilan taqqoslash orqali sonli hisoblab chiqilgan.



10-rasm: Magnitlangan zarrachaning ISCO radiusining magnit zaryadlangan muntazam va RN qora o‘ralari atrofidagi bog’liqligi.



11-rasm. Magnitlanish parametri *b* ning turli qiymatlari uchun muntazam qora o‘raning magnit zaryadidan energiya samaradorligining bog’liqligi.

Markaziy qora o‘raga tushadigan zarracha orqali akretsion diskidan energiya ajralib chiqishi samaradorligining qora o‘ra zaryadidan bog’liqligi 11-rasmda ko‘rsatilgan va olingan natijalarni Kerr va RN qora o‘raning natijalari bilan taqqosladik. Zaryadning o‘sishi bilan samaradorlik ortib borayotganini ko‘rish mumkin. Bundan tashqari, RN qora o‘ra va regulyar qora o‘ra effektlarining farqi magnit zaryadning yuqori qiymatlarida ko‘rinadi, xuddi shunday, magnit birlashtirish parametri yuqori qiymatlarni olganida farq yo‘qoladi. Magnit bog’lanish parametri $b = 10.2$ bo‘lganda samaradorlik Kerr modelidagiga qaraganda tezroq o‘sishini ko‘rsatdik.

Biz yo‘qolmaydigan magnit monopol bilan tavsiflangan magnit zaryadlangan zarrachaning dinamikasini o‘rganamiz. Oldingi boblardagi kabi mantiqqa amal qilib, biz harakat tenglamasini tuzamiz. Magnit zaryadlangan va elektr neytral zarra uchun Gamilton-Yakobi harakat tenglamasi quyidagi ko‘rinishga ega

$$g^{\alpha\beta}\left(\frac{\partial S}{\partial x^{\alpha}} + iq_m A^{\star}_{\alpha}\right)\left(\frac{\partial S}{\partial x^{\beta}} + iq_m A^{\star}_{\beta}\right) = -m^2, \tag{43}$$

bu yerda $\boldsymbol{q_m}$ - sinov zarrasining magnit zaryadi va to‘rt vektor $\boldsymbol{A^{\star}_{\alpha}}$ quyidagi yo‘qolmaydigan komponentga ega bo‘lgan ikki tomonlama vektor potentsialini belgilaydi

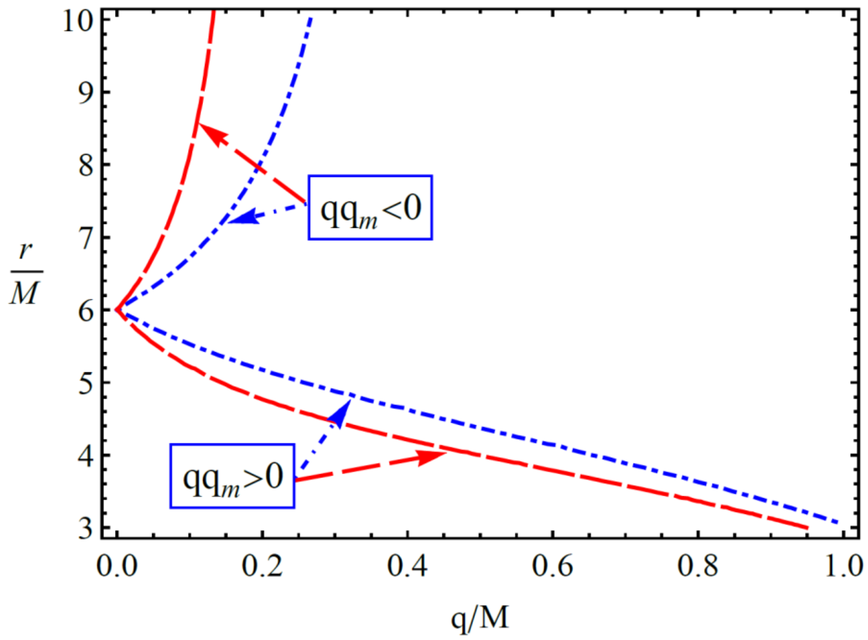
$$A^{\star}_{t} = -\frac{iq}{r} \tag{44}$$

Ekvator tekisligida harakatlanuvchi magnit zaryadlangan zarrachaning radial harakatining effektiv potensialini ($\theta = \pi/2$) quyidagi shaklda yozish mumkin.

$$V_{\text{eff}} = \frac{qq_m}{r} + \sqrt{\left(1 - \frac{2M}{r}e^{-\frac{q^2}{2Mr}}\right)\left(1 + \frac{\mathcal{L}^2}{r^2}\right)}. \tag{45}$$

$\partial_{rr}V_{\text{eff}} = 0$ shartining $r = r_{\text{isco}}$ ga nisbatan yechilishi 12-rasmda ko‘rsatilganidek ISCO radiusi va fazo-vaqt metrikasi parametrlari o‘rtasidagi maqsadli munosabatni tekshirilayotgan zarrachaning magnit zaryadi bilan birga olish imkonini beradi. Sinov zarrachasining magnit zaryad parametrining berilgan diapazonida ushbu parametr va

ISCO radiusi o‘rtasidagi deyarli radial bog’liqlikni ko‘rish mumkin. Shuni ta'kidlash kerak-ki, neytral zarrachaning harakati bilan solishtirganda, bu magnit maydon va magnit zaryadlangan sinov zarrasi o‘rtasidagi o‘zaro ta'sir tortishish obyektining tortishish kuchidan ancha zaif ekanligi bilan bog’liq. Rasmdagi chiziqlar shakli jihatidan sezilarli darajada farq qilmaydi.



12-rasm. Zaryadlangan zarrachalarning ISCO radiusining regulyar qora o‘ra zaryadiga bog’liqligi.

XULOSA

“Zaryadlangan qora o‘ralar atrofida zaryadlangan zarrachalar dinamikasi va energetik jarayonlar” dissertatsiyasi doirasida olib borilgan tadqiqot natijalariga ko‘ra quyidagi xulosalar chiqarildi:

1. Sinxrotron nurlanishining intensivligi, shuningdek energiyani chiqarish samaradorligi Eynshteyn-Maksvell skalyar nazariyasida massasiz skalyar maydon qiymatlarining kamayishi bilan oshadi;

2. Ionlanish nuqtasidan uzoqlashish elektr Penrose jarayonining energiya chiqarish samaradorligini pasaytiradi. O‘lchovsiz parametr l-ning ortishi samaradorligini oshiradi. Kalb-Ramond gravitatsiyasida zaryadlangan zarrachalarning to‘qnashuvi vaqtida o‘lchovsiz parametr l ortib borishi bilan kritik burchak momenti kamayadi;

3. Regulyar qora o‘ra uchun markaziy qora o‘raga tushadigan zarracha orqali akkretsiya diskidan energiya ajralib chiqish samaradorligining qora o‘ra zaryadiga bog’liqligi olingan. Zaryadning oshishi bilan samaradorlik oshishi aniqlandi. Zarrachalarning magnitlanish parametri b=10,2 bilan samaradorlik Kerr modeliga qaraganda tezroq oshishi ko‘rsatilgan.

SCIENTIFIC COUNCIL DSc.03/31.03.2022.T/FM.10.04 ON AWARD OF SCIENTIFIC DEGREE AT THE INSTITUTE OF FUNDAMENTAL AND APPLIED RESEARCH "TIIAME" NATIONAL RESEARCH UNIVERSITY

ULUGH BEG ASTRONOMICAL INSTITUTE

KURBONOV NURIDDIN ABDURASHIDOVICH

DYNAMICS OF CHARGED PARTICLES AND ENERGETIC PROCESSES IN THE FIELD OF CHARGED BLACK HOLES

01.03.01 - Astronomy
01.03.02- Astrophysics and space physics

DISSERTATION ABSTRACT OF THE DOCTOR OF PHILOSOPHY (PhD) ON PHYSICAL AND MATHEMATICAL SCIENCES

Tashkent – 2024

The theme of the Doctor of Philosophy (PhD) dissertation on physical and mathematical sciences was registered by the Supreme Attestation Commission of the Cabinet of Ministers of the Republic of Uzbekistan under B2024.2.PhD/FM1082.

The dissertation was prepared at the Ulugh Beg Astronomical Institute of the Uzbek Academy of Science. The abstract is posted in three languages (Uzbek, English, and Russian (resume)) on the website (https://www.ifar.uz) and the "Ziyonet" information and educational portal (www.ziyonet.uz).

Scientific consultants:	**Toshmatov Bobir Abdumanonovich** doctor of sciences in physics and mathematics
	Rayimbaev Djavlanbek Radjapbaevich doctor of sciences in physics and mathematics
Official opponents:	**Atamurotov Farruh Shukhratovich** doctor of sciences in physics and mathematics
	Juraeva Nozima Bobomurod kizi doctor of philosophy (PhD) on physical and mathematical sciences
Leading organization:	**Al-Farabi Kazakh National University**

The defense of the dissertation will be held at the meeting of the Scientific Council No. DSc.03/31.03.2022.T/FM.10.04 at the Institute of Fundamental and Applied Research under the "TIIAME" National Research University on _______ _____ 20__ at ____. (Address: Institute of Fundamental and Applied Research, 39, Qori Niyazi street, Tashkent city, 100000. Hall 108; Ph.: (+99871) 237-09-61; fax (+998 71) 234-09-62; e-mail: info@ifar.uz).

The dissertation can be found at the Information Resource Center of the Institute of Fundamental and Applied Research under the "TIIAME" National Research University (registered under number ___). (Address: Institute of Fundamental and Applied Research, 39, Qori Niyazi street, Tashkent city, 100000. Hall 108; Ph.: (+99871) 237-09-61.

Abstract of dissertation sent out on « _____ » ________ 20__ year
(Mailing report № ___ on « ___ » _________ 20__ year)

B.J. Ahmedov
Chairman of the Scientific Council on Award of Scientific Degrees, DSc, Academician

Sh.N. Mardonov
Scientific Secretary of Scientific Council on Award of Scientific Degrees, DSc

A.B. Abdikamalov
Chairman of the Scientific Seminar of the Scientific Council on Award of Scientific Degrees, DSc

\INTRODUCTION (Annotation of PhD dissertation)
Introduction

Relevance and necessity of the dissertation topic. The study of charged particles and their dynamics in the field of charged black holes is a highly topical and significant area of research in modern astrophysics and fundamental physics. Charged black holes, described by solutions such as the Reissner-Nordström and Kerr-Newman metrics, provide a unique laboratory to explore the interplay between gravitational, electromagnetic, and inertial forces in extreme conditions. These environments are critical for understanding the behavior of matter and radiation near compact objects and for probing potential deviations from General Relativity, especially in the presence of strong electromagnetic fields.

The investigation of energetic processes, such as particle acceleration and the generation of high-energy emissions, has profound implications for astrophysical phenomena. Many observed phenomena, including relativistic jets, gamma-ray bursts, and high-energy cosmic rays, may involve mechanisms rooted in charged particle dynamics around charged black holes. Furthermore, these studies contribute to our understanding of plasma physics in extreme environments, which is essential for interpreting data from advanced observational facilities like the Event Horizon Telescope and space-based X-ray and gamma-ray telescopes.

By addressing these topics, this dissertation aligns with contemporary efforts to link theoretical models with observations, advancing our understanding of black hole environments and their energetic signatures. This work not only deepens insights into high-energy astrophysical processes but also contributes to the broader goal of testing fundamental theories under extreme conditions, making it highly relevant in both theoretical and observational contexts. In our country, there is also much attention being paid to studies of the radiation mechanisms in the accretion disk of BHs as well as optical and energetic processes around the BHs, and theoretical studies of gravity theories and testing them based on observational data.

This dissertation work corresponds to the tasks by the following state regulatory documents: Decree of the President of the Republic of Uzbekistan No. UP-4947 "On the Strategy of Actions for the Further Development of the Republic of Uzbekistan" dated February 07, 2017, Decree of the President of the Republic of Uzbekistan No. PP-2789 "On Measures for Further Improvement of Academy of Sciences, organization, management, and financing of research activities "from 18.02.2017.

Relevance of the research to the priority areas of science and technology development of the Republic of Uzbekistan.

Relevance of the research to the priority areas of science and technology development of the Republic of Uzbekistan. The dissertation research has been carried out in accordance with the priority areas of science and technology in the Republic of Uzbekistan.

Review of international scientific research on the topic of the dissertation.

Black holes in higher-dimensional theories with dilaton fields were studied by the British physicist G.W. Gibbons (Nuclear Physics B, vol. 298). Solutions for black holes of the Einstein-Maxwell-scalar theory were investigated by Chinese scientists S. Yu, J. Qiu, and C. Gao (Classical Quantum Gravity, Volume 38, Number 10).

The first works on Kalb-Ramond gravity were published by M. Kalb and P. Ramond (Physical Review D, vol. 9, no. 8), and solutions for black holes in this gravity were published by Chinese scientists Z.-Q. Duan, J.-Y. Zhao, and K. Yang (Eur. Phys. J. C 84, 798).

Energy processes have been studied by a number of scientists - the Penrose process (Nuovo Cimento Rivista Serie, vol. 1, 1969), the magnetic Penrose process (Mon. Not. R. Astron. Soc, vol. 478) and the electric Penrose process (Phys. Rev. D, vol. 104, no. 8).

Problem comprehension level

In 1969, the famous British physicist (now Nobel laureate) Roger Penrose proposed a mechanism that described the process of energy release from a rotating black hole. Later, N.Dadhich proposed a mechanism for energy release called the "magnetic Penrose process". In 2021, Arman Tursunov wrote a paper related to the electric Penrose process. The study of these processes was widely carried out in Europe (R. Penrose, Z. Stucklik, and M. Kolos, etc.), in India (N.Dadhich, S. M. Wagh, V. Dhurandhar, etc.) and by scientists from other countries of the world. In our republic, the theoretical studies on optical and energetic processes around BHs in various gravity theories have also potentially been studied by B. Ahmedov, A. Abdujabbarov, J. Rayimbaev, A. Tursunov, S. Shaymatov, etc. However, in their research, the study of the mechanism of energy release from the BH was investigated within the framework of the general theory of relativity. In my dissertation work, this process was considered in an alternative theory of gravity (a black holes in the Einstein-Maxwell-scalar (EMS) theory and in Kalb-Ramond (KR) gravity).

However,

Connection of the topic of the dissertation with the scientific research of the higher educational/research institutions, where the dissertation was carried out.

The dissertation was done on the research topics of Ulugh Beg Astronomical institute and in the framework of the scientific projects of the Nuclear Physics Institute, Uzbek Academy of Sciences: F-FA-2021-510 "Investigations of nuclear matter of neutron stars in modified gravity" (2021-2026).

The purpose of the study

is to study energy processes and the motion of charged particles around black holes.

The tasks of the research:

to study the charged particle dynamics around charged black holes in Einstein-Maxwell-scalar theory;

to investigate the electric Penrose process around a charged black hole in Einstein-Maxwell-scalar gravity;

to examine the Penrose process in Kalb-Ramond BH;

to study the curvature invariants, event horizon, and electric field properties of the spacetime around the regular black hole.

The objects of the research are charged BHs in Alternative Theory Gravity and charged regular BH.

The research subjects are the electric Penrose process in Einstein-Maxwell-scalar theory and Kalb-Ramond gravity.

The research methods are the mathematical apparatus of GR & numerical statistics methods.

The scientific novelty of the research is as follows:

for the first time, decreasing the intensity of synchrotron radiation by charged particles and the efficiency of the electric Penrose process around charged black hole due to the massless scalar field in Einstein-Maxwell-scalar theory theory is shown;

for the first time, it is shown that for the same values of the black hole charge, the efficiency of the Penrose electric process in the Kalb-Ramond gravity is higher than for black holes in general relativity;

for the first time, in the Novikov-Thorne model, considering magnetized particles in an accretion disk around regular BHs, energy release efficiency exceeds the Kerr black holes (20%), reaching 22%.

it is shown that the inner radius of the accretion disk of black holes is the same for nonlinear and linear electrodynamics at a large value of the particle magnetization parameter.

Practical results of the research are as follows:

the synchrotron radiation of charged particles around a charged black hole in the theory Einstein-Maxwell-scalar is investigated and the radiation intensity is compared with the Reissner-Nordström black hole;

the results of the study of the collision of charged particles were obtained and the critical angular momentum for an electrically charged black hole in the Kalb-Ramond gravity is found. Shown that oppositely (relative to the charging of the BH) charged particles have a greater critical angular momentum due to the Coulomb interaction;

the influence of the magnetic moment on the motion of magnetized particles in the vicinity of a regular black hole is studied and its extremum is found for a realistic astrophysical system.

Reliability of the research results is provided by the following:

advanced techniques in general relativity and astrophysics, coupled with efficient numerical methods and algorithms, are employed;

the theoretical results of other authors are carefully reviewed for consistency;

the conclusions are highly consistent with the foundational principles of the field theory of compact gravitational objects.

The scientific and practical significance of the research results

the obtained results for a charged black hole in the Einstein-Maxwell-scalar theory can provide information on how a massless scalar field affects the efficiency of energy release from a black hole;

the study of the influence of the Kalb-Ramond field on the electric Penrose process and particle collisions around charged black holes in Kalb-Ramond gravity can be useful in studying the properties of the space-time of black holes in an alternative theory of gravity;

the results of the study of the motion of magnetized particles and their energy processes around magnetically charged regular black holes can be used in studying the accretion disk consisting of magnetized particles and the motion of magnetized neutron stars around the center of the galaxy.

Implementation of research results

The results of the study of energy processes and dynamics of charged around charged black holes in various theories of gravity were applied as follows:

the results in determining circular orbits for magnetized and magnetically charged particles around charged regular BHs has been used by several authors in studying the properties of spacetime around black holes, as well as gravitational models (Physical Review D 108(4), 044030, (2023), European Physical Journal C83(11), 989, (2023), European Physical Journal C 84(2),203, (2024), Physics of the Dark Universe 46,101616, (2024)). The results were provided to make it possible to analyze the motion of magnetized and magnetically charged particles around black holes based on theoretical data for black holes;

the results of studying the energy processes around charged black holes were used by a number of authors in studying the properties of space-time for an alternative theory of gravity (European Physical Journal Plus 138(7), 635, (2023), Chinese Physics C 48(2), 025101, (2024), European Physical Journal C 84(4), 420, (2024), European Physical Journal C 84(8),829, (2024), European Physical Journal C 84(9),964, (2024)). The results are used to analyze the circular orbits of charged particles and their energy properties in the field of charged black holes.

Approval of research results in The dissertation results have been discussed in 1 international conference (ICTPA-2024), 2 national scientific conferences and regular weekly Uzbek-Kazakh seminars on theoretical physics and astrophysics.

Publication of research results: The dissertation results are obtained from 7 scientific papers, four published in refereed journals (EPJC Q1, IJMPD Q2).

Volume and structure of the dissertation: The dissertation is 101 pages long and consists of an introduction, three chapters, a conclusion, and a list of references.

List of published articles the dissertation chapters were compiled using the results of the following published articles:

THE MAIN CONTENT OF THE DISSERTATION.

The introductory part shows the dissertation's relevance and importance, its goals and objectives, and its scientific and practical novelty. In contrast, the theoretical and practical significance of the obtained results is discussed.

In the present section 1 titled “**Synchrotron radiation and Penrose process near charged black holes in Einstein-Maxwell-scalar theory**”, we will briefly review charged black hole solutions in Einstein-Maxwell-scalar (EMS) theory. The action is given as

$$S = \int d^4x\sqrt{-g}\left[R - 2\nabla_\alpha\phi\nabla^\alpha\phi - K(\phi)F_{\alpha\beta}F^{\alpha\beta}\right]$$

where ∇_α is the covariant derivative, g is the determinant of $g_{\mu\nu}$, R is the Ricci scalar of the spacetime curvature, ϕ is a massless scalar field, $F_{\alpha\beta}$ is the electromagnetic field tensor, $K(\phi)$ is the coupling function between the dilaton and the electromagnetic fields.

The general form of the black hole solution has been obtained

$$ds^2 = -U(r)dt^2 + \frac{dr^2}{U(r)} + f(r)(d\theta^2 + \sin^2\theta\, d\varphi^2) \tag{1}$$

where $U(r)$ and $f(r)$ are radial functions which have the special forms for the function $K(\phi)$

$$K(\phi) = \frac{2e^{2\phi}}{\beta e^{4\phi} + \beta - 2\gamma}\ , \tag{2}$$

and obtained the solution in the form

$$f(r) = r^2\left(1 + \frac{\gamma Q^2}{Mr}\right),$$

$$U(r) = 1 - \frac{2M}{r} + \frac{\beta Q^2}{f(r)}. \tag{3}$$

and the total mass M and electric charge Q. $\beta = 0$ is the Schwarzschild limit, and $\gamma = 0$ and $\beta = 1$ is Reissner-Nordström (RN) one.

It is worth noting that it has been assumed that the vector and the dilaton fields depend on the radial coordinate only as

$$A_t(r) = \frac{Q}{r}\left[\gamma - \frac{\beta}{2}\left(1 + \frac{r^2}{f(r)}\right)\right]. \tag{4}$$

We investigate the synchrotron radiation coming out of the charged particles which are accelerated due to electromagnetic forces (Coulomb and Lorentz forces) in the surrounding of charged black holes in EMS theory. The charged particles orbiting the charged EMS black hole emit synchrotron radiation by the particles that is accelerated to relativistic velocities. In order to investigate the synchrotron radiation of the charged particle with orbital motion in the spacetime of the EMS black hole, we use the expression

$$I = \frac{2q^2}{3}\omega_\alpha\omega^\alpha, \tag{5}$$

where ω_α is the acceleration of the charged particles orbiting the black hole measured by a proper observer:

$$\omega^\alpha = \frac{q}{m}F^\alpha_\beta u^\beta, \qquad \omega_\alpha u^\alpha = 0. \tag{6}$$

The second part of Eq. (6) implies the velocity of the particle is perpendicular to its acceleration. The charged particle moving along the stable circular orbit with velocity components: $u^\alpha = u^t(1,0,0,\Omega)$, and the acceleration $\omega^\alpha = \left(0, \omega^r, \omega^\theta, 0\right)$. The non-zero components of the particle acceleration vector are

$$\omega_r = \frac{q\Omega F_{rt}}{m\sqrt{-g_{tt} - \Omega^2 g_{\phi\phi}}}, \qquad \omega_\theta = 0. \tag{7}$$

The intensity of the radiation can be easily calculated using Eq. (6) in the following form:

$$I = -\frac{2q^4}{3m^2}\frac{g^{rr}F_{rt}^2}{g_{tt}+\Omega^2 g_{\phi\phi}}. \tag{8}$$

Figure 1 shows the ratios of intensities of synchrotron radiation by charged particles accelerated in the spacetime of a charged black hole in EMS gravity and in an RN black hole with the same charges. The figure demonstrates that the radiation intensity increases with increasing values of the β parameter (left panel). In addition, the intensity decreases with positive values of γ and increases with negative values (central panel). In this way, the dependence of the particle charge was studied. It is shown that decreasing the particle charge leads to an increase in the radiation intensity (right panel).

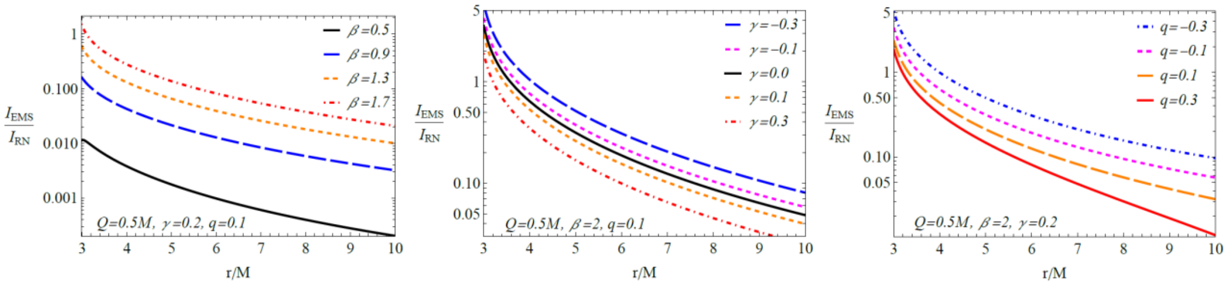


Figure 1: Comparison of the intensity of synchrotron radiation by charged particles orbiting charged black holes in EMS theory and RN black holes. Here, we analyze the intensity ratios I_{EMS}/I_{RN} as a function of radial coordinates for different values of EMS parameters.

Now, we derive the equation for the angular velocity of the decayed particles measured by a static distant observer located at infinity $\Omega = d\phi/dt$ as follows

$$\Omega = \pm\frac{1}{u^t\sqrt{f(r)}}\sqrt{(u^t)^2\left[U(r)-\frac{v^2}{U(r)}\right]-k}\,. \tag{9}$$

The possible values of Ω are limited by,

$$\Omega_- \leq \Omega \leq \Omega_+, \quad \Omega_\pm = \pm\sqrt{\frac{U(r)}{f(r)}}\,. \tag{10}$$

corresponding to the Keplerian orbits.

We consider a scenario in which a charged particle (1) approaches a charged black hole in EMS theory from infinity and decays into two charged parts (2 and 3) in the vicinity of the event horizon in the equatorial plane. We assume that the decay process satisfies the conservation laws of energy, momentum, and charge

$$E_1 = E_2 + E_3,\;\; L_1 = L_2 + L_3,\;\; q_1 = q_2 + q_3, \tag{11}$$

$$m_1\dot{r}_1 = m_2\dot{r}_2 + m_3\dot{r}_3, m_1 \geq m_2 + m_3, \tag{12}$$

where the over dots stand for derivatives by the proper time (τ). Using the Eqs.(11) and (12), we can find the following equation

$$m_1 u_1^{\phi} = m_2 u_2^{\phi} + m_3 u_3^{\phi}, \tag{13}$$

where $u^{\phi} = \Omega u^{t} = \Omega e/f(r)$, $e_i = (E_i + q_i A_t)/m_i$, with $i = 1,2,3$ indicating the particle's number, the equation (13) will take the following form

$$\Omega_1 m_1 e_1 = \Omega_2 m_2 e_2 + \Omega_3 m_3 e_3. \tag{14}$$

where $\Omega_i = d\phi_i/dt\$$ is an angular velocity of i^{th} particle given by (9), with restricted values (10). By solving the Eq.(14) we can find the energy of one of the particles, e.g. E3

$$E_3 = \frac{\Omega_1 - \Omega_2}{\Omega_3 - \Omega_2}(E_1 + q_1 A_t) - q_3 A_t. \tag{15}$$

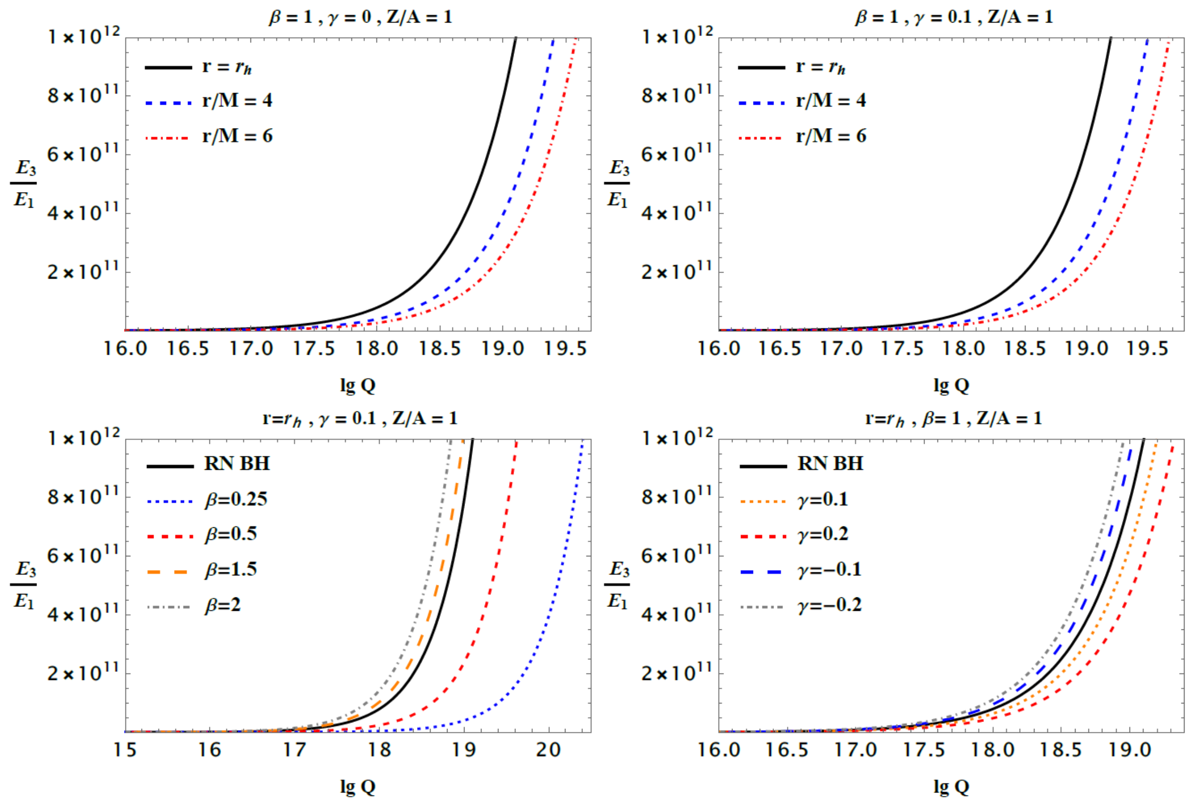


Figure 2: Ratio of energies of ionized and neutral particles plotted against the black hole charge Q for different values of spacetime parameters. The black solid line corresponds to RN BH case at β = 1 and γ = 0 in the bottom panels of the figure.

We provide graphical analyses of E_3/E_1 dependency on the EMS parameters in Fig.2. In Fig.2 we plotted the dependence of the efficiency of the acceleration mechanism (ratio of the ionized and neutral particle with $Z/A = 1$) on the charge of the black hole. The efficiency of the acceleration mechanism increases with the charge of the black hole and decreases slightly as the distance between the black hole and the ionization point increases (as shown in the top panel of Fig.2). Moreover, the efficiency corresponding to a certain value of the black hole's charge increases as the β parameter increases and decreases as the γ parameter increases (as shown in the bottom panel of Fig.2).

The critical value of angular momentum can be determined by two conditions: (a) $\dot{r} = 0$ and (b) $d\dot{r}/dr = 0$. This is illustrated in Fig. 3. An increase in the angular momentum causes the square of the radial velocity to be negative implying the particles can no longer approach the central object from that value. Therefore, we investigated the allowed values of the angular momentum and determined the critical values.

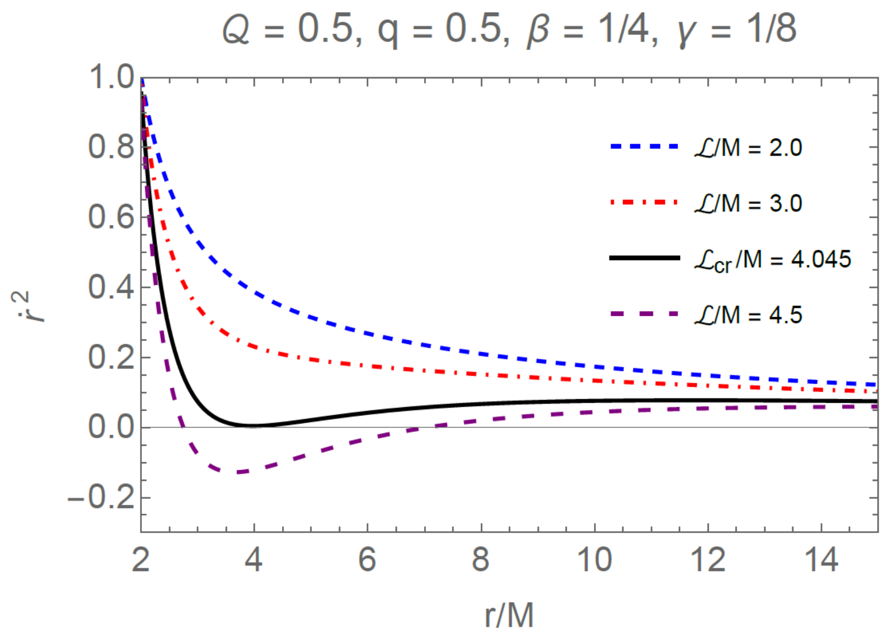


Figure 3: Radial dependence of the square of radial velocity for different values of angular momentum of the particle.

Figure 4 presents the dependence of the critical angular momentum on the EMS parameters for various values of the black hole's parameters and particle charge. The top three panels show the critical angular momentum as a function of the magnetic parameter (β) for different values of the γ parameter. The left panel shows that increasing γ decreases the permissible value of angular momentum, and there is a linear relationship with the β parameter. The middle panel illustrates that the linearity is disrupted for larger values of black hole charge. The right panel depicts the effect of varying the particle charge. The bottom panels show the angular momentum as a function of γ. In most cases, the angular momentum is linearly dependent on γ, with an increase in γ causing a decrease in angular momentum, opposite to the behavior with the β parameter. The middle and right panels replicate the behaviour of the top panel by varying the black hole and particle charge, respectively. The bottom-left figure shows the plot by varying the magnetic parameter β of the black hole.

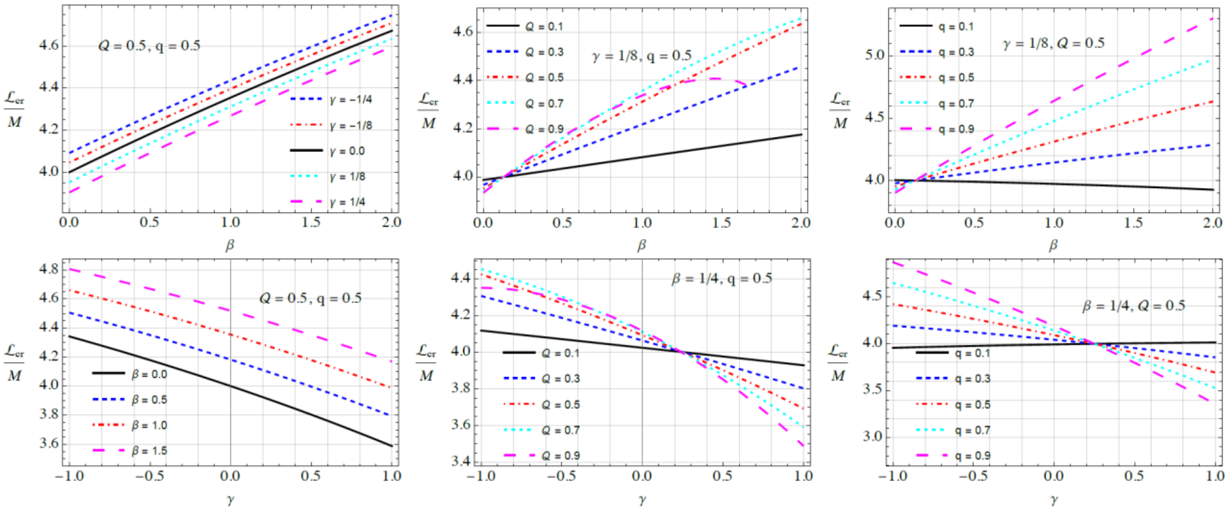


Figure 4: Dependence of the critical angular momentum on β (top panels) and γ (bottom panels) for different values of the black hole and particle parameters.

In the second section, named "**Electric Penrose and collisions of charged particles near charged black holes in Kalb-Ramond gravity**", we focus on deriving the equation of motion of electrically charged particles around the static-charged BHs. The charged BH solution with spherically symmetric spacetime geometry with using through spherical coordinates, ($x^{\alpha} = \{t, r, \theta, \phi\}$) in the following form,

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\,, \tag{16}$$

where the radial functions $f(r)$ is given by

$$f(r) = \frac{1}{1-l} - \frac{2M}{r} + \frac{Q^2}{r^2(1-l)^2}\,. \tag{17}$$

Here, M represents the total mass of the BH, whereas Q represents its electric charge. Classical gravitational measurements undertaken in the Solar System have shown that the dimensionless parameter l, which represents the Lorentz-violating impact generated by the non-zero vacuum expectation value of the Kalb-Ramond (KR) field, must have a very small value. When $l = 0$, it will converge to the standard RN-like metric.

In Fig.5, we show relationships between extreme BH charge and the KR parameter. The light-blue shaded area implies the value of Q and l in which the spacetime (17) has an event horizon that belongs to a BH. In the values of Q and l out of the shaded area, the BH turns into an object without an event horizon.

It also is worth noting that it has been assumed that the vector and the dilaton fields depend on the radial coordinate only, in the following form:

$$A_t(r) = \frac{Q}{(1-l)r}. \tag{18}$$

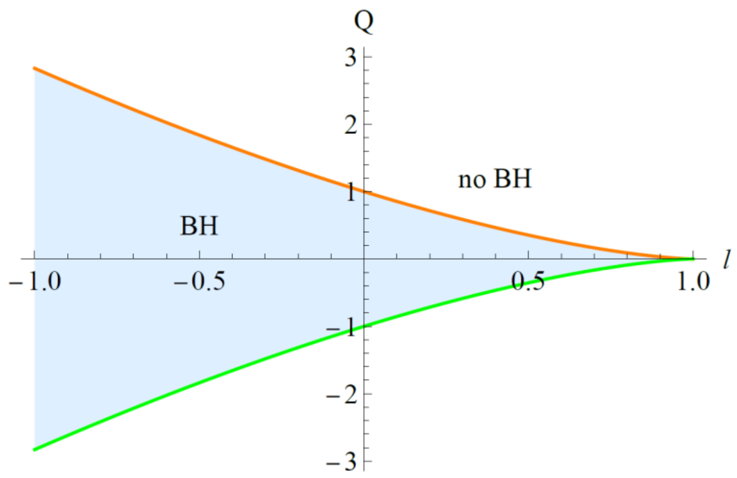


Figure 5: The dependence of extreme values of the BH charge Q from l.

We will deduce an expression describing the angular velocity of the decayed particles as seen by a static observer positioned at an infinite distance. For this, we have

$$\zeta = \pm\frac{1}{v^t r}\sqrt{(v^t)^2\left[f(r) - \frac{\mu^2}{f(r)}\right] - \lambda}\,. \tag{19}$$

The range of potential values for ζ is limited by,

$$\zeta_- \leq \zeta \leq \zeta_+, \qquad \zeta_\pm = \pm\sqrt{\frac{f(r)}{r^2}}\,, \tag{20}$$

that corresponds to the Keplerian orbits.

Subsequently, we examine a situation wherein a charged particle approaches a charged BH from infinity in Kalb-Ramond gravity theory and undergoes breakdown into two charged particles in the equatorial plane close to the event horizon. We consider that the conservation rules of energy, momentum, and charge are satisfied by the decay process (10-11).

Using the above equations, we have

$$m_1 v_1^\phi = m_2 v_2^\phi + m_3 v_3^\phi, \tag{21}$$

where $v^\phi = \zeta v^t = \zeta e/r^2$, $e_i = (E_i + q_i A_t)/m_i$ and $i = 1,2,3$ denotes the number of particles, The equation (21) can be expressed as follows,

$$\zeta_1 m_1 e_1 = \zeta_2 m_2 e_2 + \zeta_3 m_3 e_3. \tag{22}$$

The angular velocity of the ith particle, denoted by $\zeta_i = d\phi_i/dt$, is determined by equation (19) and is subject to the limitations specified in equation (20). The determination of the energy of a particle, such as E_3, is possible by solving Equation (22). We have

$$E_3 = \frac{\zeta_1 - \zeta_2}{\zeta_3 - \zeta_2}(E_1 + q_1 A_t) - q_3 A_t. \tag{23}$$

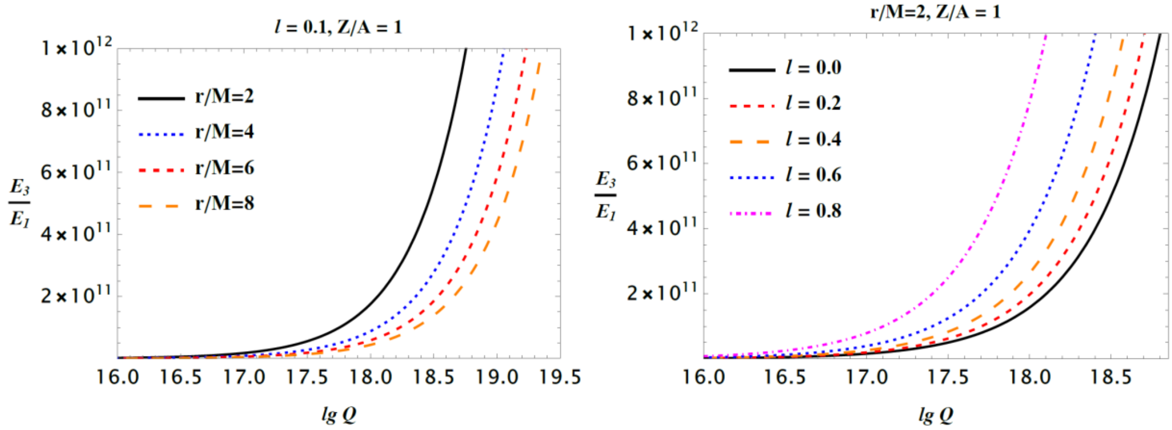


Figure 6: Ratio of energies plotted against the BH charge Q for different values of spacetime parameters. $l = 0$ shows the standard RN BH solution (right panel) results.

We may compute the final equation for E_3/E_1 by directly expressing the BH mass and the speed of light in terms of the time component of the electromagnetic four potential and metric functions. This equation is intricate and challenging to solve. Consequently, we visually represent its reliance on the BH parameters in Figure 6. Figure 6 (left panel) displays the efficiency of the acceleration mechanism, which is the ratio of the energies of ionized and infalling particles with $Z/A = 1$. The figure shows this efficiency at different ionization sites as a function of the BH's charge per solar mass. The efficiency significantly increases as the charge of the BH increases. Moreover, it declines as the distance between the BH and the ionization point increases. In case of changing the parameter l (right panel), the efficiency increases with the increase of this parameter.

The general expression for the energy of the center of mass can be expressed as

$$\{E_c, 0,0,0\} = m_1 u_1^{\mu} + m_2 u_2^{\mu}, \tag{24}$$

The variables u_1^{α} and u_2^{β} represent the four-velocity of the two particles involved in the collision, with masses m_1 and m_2 correspondingly. It is straightforward to compute the square of the center of mass energy, as described in equation (24), and get the result.

$$E_c^2 = m_1^2 + m_2^2 - 2m_1 m_2 g_{\mu\nu} u^{\mu} u^{\nu}, \tag{25}$$

$$\frac{E_c^2}{m_1 m_2} = \frac{m_1}{m_2} + \frac{m_2}{m_1} - 2g_{\mu\nu} u_1^{\mu} u_2^{\nu}. \tag{26}$$

If the masses of the colliding particles are denoted as $m_1 = Am$ and $m_2 = Bm$. Then we have

$$\frac{E_{cm}^2}{m^2 c^4} = A^2 + B^2 - 2g_{\mu\nu} u_1^{\mu} u_2^{\nu}. \tag{27}$$

We will then investigate the collision of particles with identical initial energies and masses ($E_1 = E_2 = m$). We shall examine the acceleration of charged particles near a Kalb-Ramond BH by applying the standard equation for the center of mass energy of two colliding particles of equal mass. As a consequence, the equation for the center-of-mass energy becomes.

$$\varepsilon_c^2 = \frac{E_c^2}{4m^2c^4} = 1 - g_{\alpha\beta}u_1^{\alpha}u_2^{\beta}\,. \qquad (28)$$

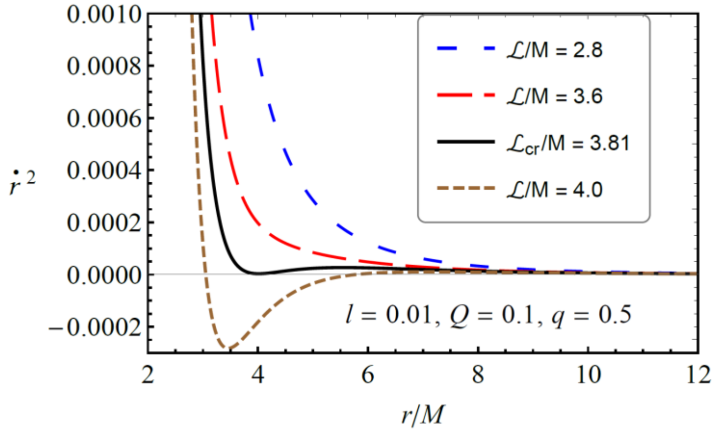


Figure 7: Radial dependence of the square of radial velocity for different values of angular momentum of the particle.

Two conditions permit the determination of the critical value of the angular momentum: (i) $\dot{r} = 0$ and (ii) $d\dot{r}/dr = 0$. Figure 7 illustrates this. A negative radial velocity results from an increase in the angular momentum. From that value, the particles cannot approach the central object. Consequently, we examined the permissible values of the angular momentum to determine the critical values. The dependency of the critical angular momentum for different values of the BH's parameters and particle charge is shown in Figure 8. The upper panels show the relationship between the critical angular momentum and the parameter (q) between different values of the parameter l (on the left) and Q (on the right). The top left panel illustrates that as the value of l increases, the allowable range of angular momentum declines, and there is a linear relation with the q parameter. Similarly, the bottom panel depicts the critical angular momentum with a BH Q charge, considering different parameters l (on the left) and q (on the right). Similar behavior can be observed for both cases.

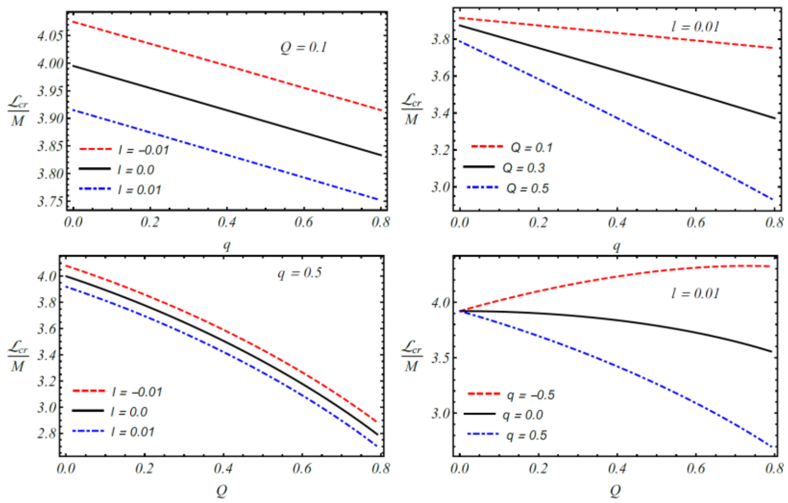


Figure 8: Dependence of the critical angular momentum on q (top panels) and Q (bottom panels) for different values of the BH and particle parameter.

In the third section, titled "**Particle dynamics in the magnetically charged regular black hole environment**", In order to obtain a regular black hole (RBH) solution in GR, one has to couple it with NED using the action in the following form

$$S = \frac{1}{16\pi} \int dx^{4\sqrt{-g}} \big(R - L(F)\big) \quad (29)$$

where $F = F^{\mu\nu} F_{\mu\nu}$ is the electromagnetic field invariant constructed using the tensor of the electromagnetic field $F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$ which is expressed by electromagnetic field potential A_{μ}.

One can obtain the RBH solution using the following form of Lagrangian

$$L(F) = 4F e^{-\left(\frac{q}{\sqrt{2}}\right)^{\frac{3}{2}} \frac{F^{\frac{1}{4}}}{M}}, \quad (30)$$

In order to obtain RBH solution, we have used $F = q^2/(2r^4)$ and the corresponding Lagrangian of a NED field in the following form

$$L(F) = \frac{2q^2}{r^4} e^{-\frac{q^2}{2Mr}}, \quad (31)$$

where q is the magnetic charge. The metric tensor for a spherically symmetric spacetime around such RBH can be expressed as

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)} dr^2 + r^2(d\theta^2 + \sin^2\theta \, d\varphi^2)$$

with the lapse function of form

$$f(r) = 1 - \frac{2M}{r} e^{-\frac{q^2}{2Mr}}, \quad (32)$$

where M is the total mass of the RBH. When $q = 0$ the solution turns to the Schwarzschild vacuum solution.

After, we perform the study of magnetized particle dynamics around a magnetically charged regular black holes described by the lapse function (32) following Homiltion-Jacobi equation. The electromagnetic four-potential has the form

$$A_{\phi} = q \cos\theta. \quad (33)$$

Using potential (33) one may obtain the non-zero component of the electromagnetic field tensor as

$$F_{\theta\phi} = -q \sin\theta \; . \quad (34)$$

The orthonormal radial component of magnetic field generated by the magnetic charge of the regular BH can be written as

$$B^{\hat{r}} = \frac{q}{r^2} \; , \quad (35)$$

which has the form the same as Newtonian.

For the dynamics of a magnetized particle around a magnetically charged regular black hole, we assume that the direction of the magnetic dipole moment of the particle is parallel to the equatorial plane, as well as to the magnetic field of the black hole. The assumption implies that the magnetic dipole moment has only radial components $\mu^i = (\mu^r, 0,0)$. Other configurations of the components of the magnetic dipole moment cannot provide an equilibrium to the magnetic interaction with the maximum energy of magnetic interactions. Here, we will consider the motion of a magnetized particle in the proper observer frame of references. This chose of the reference helps to avoid the problems which are come from relative motion. Moreover, we consider the magnitude of the magnetic moment is unchanged during its circular motion.

In our previous works we have shown that the interaction term is the same in magnetized particle motion around magnetically charged BH scenarios and has the form

$$\mathcal{D}^{\alpha\beta}F_{\alpha\beta} = \frac{2\mu q}{r^2}\ , \tag{36}$$

where $\mathcal{D}^{\alpha\beta} = \eta^{\alpha\beta\gamma\rho}\mu_\gamma u_\rho$ is polarization tensor, μ_γ and u_ρ are four-magnetic dipole momentum and velocity of the magnetized particles. The part $\mathcal{D}^{\alpha\beta}F_{\alpha\beta}$ describes interaction between magnetic fields of the magnetized particle and RBH. The magnetic field generated by magnetically charged BHs has axial symmetric behavior and does not break the spacetime symmetry, letting the two quantities: the energy and the angular momentum to be conserved.

We investigate the radial motion of a magnetized particle at the equatorial plane, where $\theta = \pi/2$, with $p_\theta = 0$ around magnetically charged, the regular black hole. The radial equation of motion has the following form

$$\dot{r}^2 = \mathcal{E}^2 - V_{\rm eff}(r; \mathcal{L}, b, q)\ , \tag{37}$$

where the effective potential has the form

$$V_{eff}(r, \mathcal{L}, \mathcal{B}, q) = \left(1 - \frac{2M}{r} e^{-\frac{q^2}{2Mr}}\right)\left[\left(1 - \frac{\mathcal{B}}{r^2}\right)^2 + \frac{\mathcal{L}^2}{r^2}\right], \tag{38}$$

with new introduced parameters $\mathcal{B} = \mu q/m$ and $b = \mu/(mM)$ responsible for the interaction between the magnetized particles and the magnetically charged the regular black hole to characterize the parameters of the magnetized particle and the central black hole, respectively. Here we investigate a realistic astrophysical system: a magnetized neutron star as a test magnetized particle orbiting a supermassive BH where

$$b = \frac{B_{NS}R_{NS}^3}{2m_{NS}M_{SMBH}} \approx 0.18\left(\frac{B_{NS}}{10^{12}G}\right)\left(\frac{R_{NS}}{10^6 cm}\right)\left(\frac{m_{NS}}{M_\odot}\right)^{-1}\left(\frac{M_{SMBH}}{10^6 M_\odot}\right)^{-1} \tag{39}$$

One of such astrophysical systems is the magnetar SGR (PSR) J1745−2900 (with $\mu \simeq 1.6 \times 10^{32} G \cdot cm^3$ and mass $m \approx 1.5M_\odot$) orbiting the SMBH Sgr A* ($M \simeq 3.8 \times 10^6 M_\odot$) and the approximate value for the parameter is β for the case $b \approx 10.2$.

Figure 9 illustrates radial dependence of the effective potential for radial motion of magnetized particles around extreme charged regular BH and RN BH with comparing the results that was in Schwarzschild BH case. In these plots, we used $\mathcal{L} = 4.3M$ for the angular momentum and $b = 10.2$ for the magnetized particle. One can see from the Fig.9 that the existence of magnetic charge of the BH and the magnetic interaction cause the increase of the maximum effective potential, and it is larger in extreme regular BH with compare to RN one. Meanwhile, the distance where the effective potential shifts towards to the central BH.

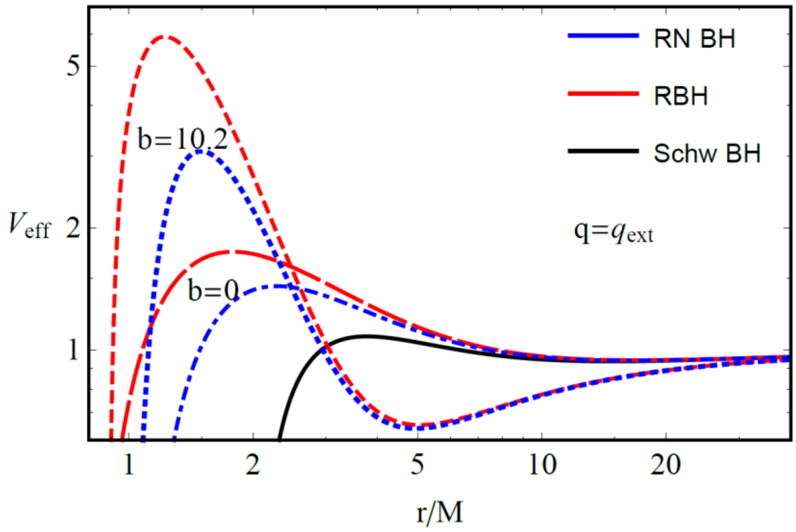


Figure 9: The radial profiles of the effective potential for radial motion of magnetized with $b = 10.2$ (in dashed lines) and neutral (in large dashed lines) particles with the specific angular momentum $\mathcal{L} = 4.3M$, around extremely charged regular and RN black holes for with the comparison of Schwarzschild case.

Specific angular momentum of the magnetized particle along the circular orbits can be expressed

$$\mathcal{L}^2 = \left(1 - b\frac{qM}{r^2}\right)\left[2bqM - \frac{(q^2-2Mr)(bMq+r^2)}{2r^2\left(e^{\frac{q^2}{2Mr}}-\frac{3M}{r}\right)+q^2}\right], \tag{40}$$

and for energy

$$\mathcal{E}^2 = \frac{2\left(e^{\frac{q^2}{2Mr}}-\frac{2M}{r}\right)^2(r^4-b^2M^2q^2)}{r^3\left(e^{\frac{q^2}{2Mr}}(q^2-6Mr)+2r^2e^{\frac{q^2}{Mr}}\right)}\ . \tag{41}$$

Figure 10 demonstrates dependence of ISCO radius of magnetized particles on the magnetic charge of RBH with comparison of the results in RN BH. One can see that the difference of RN BH and RBHs when the magnetic coupling parameter is small. However, as the increase of the coupling parameter, the difference vanishes due to saturation of the interaction between magnetized particle and the BHs magnetic field.

It is known that Novikov-Thorne model allows explanations of the existence of Keplerian orbits of accreting matter in accretion disk around an astrophysical black hole, which is well modelled as a geometrically thin disks defined by the observational properties of circular geodesic spacetime. Electromagnetic radiation in the accretion disk characterizes efficiency of energy release from the accretion disk around the BH. It means how much maximum energy can be extracted from the accretion disk by the radiation of the falling matter into the central BH from the disk. The efficiency for particles can be calculated using the following the standard expression}

$$\eta = 1 - \mathcal{E}_{\text{ISCO}}, \tag{42}$$

where $\mathcal{E}_{\text{ISCO}}$ is the energy of the particle at the ISCO which is characterized by the ratio of the binding energy (BH- particle system) and rest energy of the test particle can be calculated using the energy of the particles given in Equations (40) and (41) at ISCO. The effects of the magnetic charge of the regular BH on the efficiency are calculated numerically by plotting in Fig.11 with comparison to the energy efficiency from the RN and Kerr BHs.

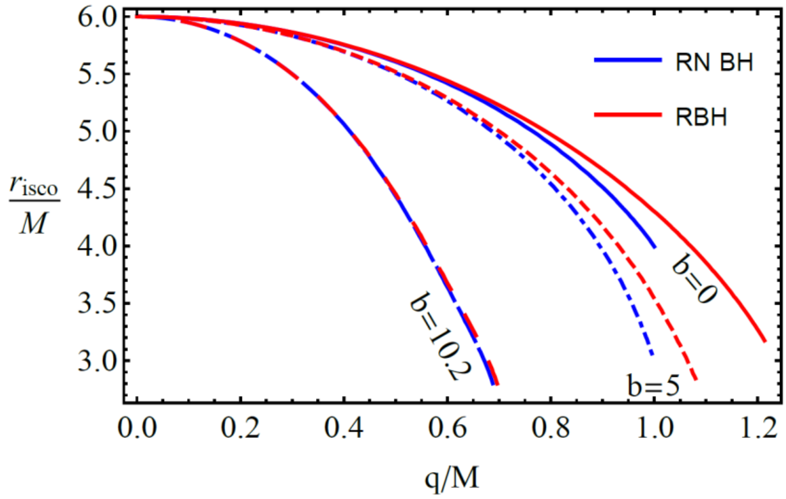


Figure 10: Dependence of ISCO radius of a magnetized particle around the magnetically charged regular and RN black holes.

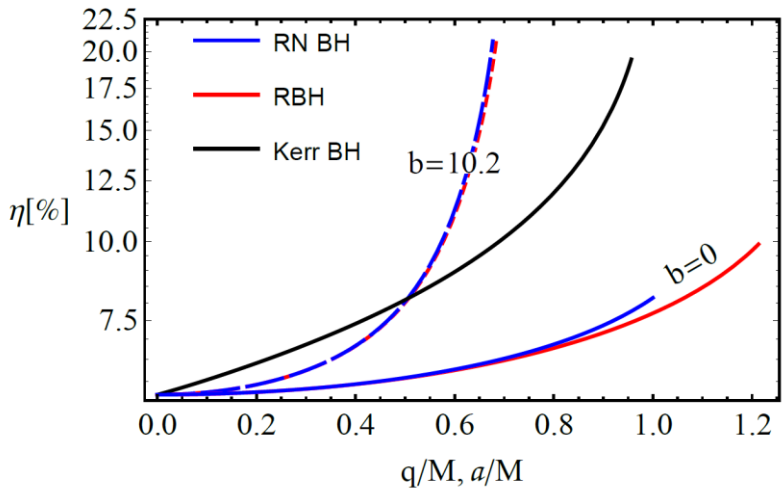


Figure 11: Dependence of the energy efficiency from magnetic charge of the regular BH for the different values of the magnetized parameter *b*.

The dependence of efficiency of energy release from accretion disk through falling particle in the central BH from the BH charge is shown in Fig.11, and we have compared the obtained results with results in Kerr and RN BHs. One can see that the efficiency increases as the charge growth. Moreover, difference of RN BH and RBH effects are seen at higher values of magnetic charge, similarly, the difference disappears when the magnetic coupling parameter takes higher values. We have shown that when the magnetic coupling parameter, $b = 10.2$ the efficiency grows faster than it is in Kerr model.

We will explore the dynamics of a magnetically charged particle characterized by non-vanishing magnetic monopole. Following the same logic as in the previous sections, we will construct the equation of motion. For a magnetically charged and electrically neutral particle, the Hamilton-Jacobi equation of motion has the form

$$g^{\alpha\beta}\left(\frac{\partial S}{\partial x^\alpha}+iq_m A^\star_\alpha\right)\left(\frac{\partial S}{\partial x^\beta}+iq_m A^\star_\beta\right)=-m^2, \tag{43}$$

where q_m is the magnetic charge of the test particle and four vector $A^\star_\alpha$ defines the dual vector potential that has the following nonvanishing component

$$A^\star_t=-\frac{iq}{r} \tag{44}$$

Effective potential of the radial motion of the magnetically charged particle moving at the equatorial plane ($\theta=\pi/2$) can be written in the following form

$$V_{\text{eff}}=\frac{qq_m}{r}+\sqrt{\left(1-\frac{2M}{r}e^{-\frac{q^2}{2Mr}}\right)\left(1+\frac{\mathcal{L}^2}{r^2}\right)}. \tag{45}$$

Solution of the condition $\partial_{rr}V_{\text{eff}}=0$ with respect to $r=r_{\text{isco}}$ allows to obtain the target relationship between the ISCO radius and the parameters of the space-time metric together with the magnetic charge of the test particle, as shown in Fig.12. In the given range of the magnetic charge parameter of the test particle, one can see the almost radial dependence between this parameter and the ISCO radius. It is useful to note that compared to the motion of a neutral particle, which is due to the fact that the interaction between the magnetic field and the magnetically charged test particle is much weaker than the gravitational force of the gravitating object. The lines in the figures do not differ significantly in shape.

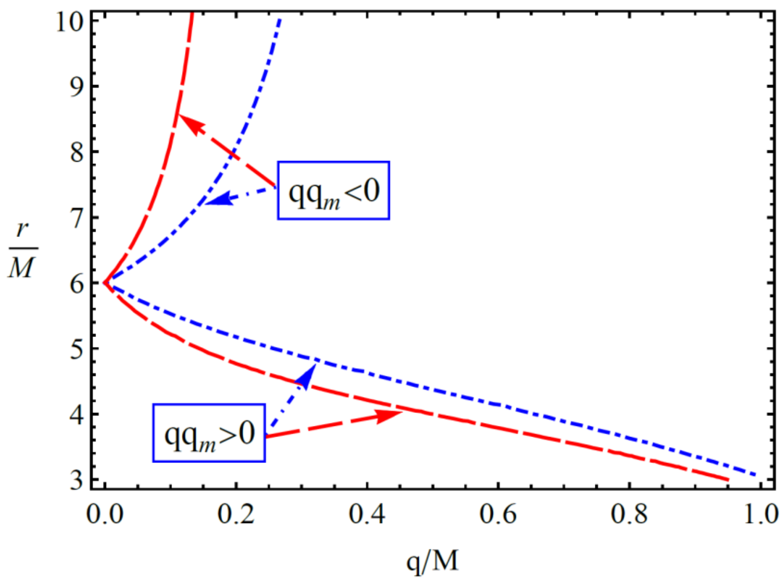


Figure 12: Dependence of ISCO radius of charged particles from RBH charge.

CONCLUSION

Based on the results of the research conducted within the framework of the dissertation "Dynamics of charged particles and energetic processes in the field of charged black holes", the following conclusions were made:

1. The intensity of synchrotron radiation, as well as the efficiency of energy release decreases with increasing value of the massless scalar field in the EMS theory;

2. The distance of the ionization point reduces the efficiency of energy release of the electric Penrose process. And an increase in the dimensionless parameter l increases it. The critical angular momentum decreases with increasing dimensionless parameter l during collisions of charged particles in gravity KR;

3. For a regular BH, the dependence of the efficiency of energy release from the accretion disk through an infalling particle in the central BH on the BH charge is obtained. It is found that the efficiency increases with increasing BH charge. It is shown that for the particle magnetization parameter b=10.2, the efficiency increases faster than in the Kerr model.

НАУЧНЫЙ СОВЕТ DSc.03/31.03.2022.T/FM.10.04 ПО ПРИСУЖДЕНИЮ УЧЕНЫХ СТЕПЕНЕЙ ПРИ ИНСТИТУТЕ ФУНДАМЕНТАЛЬНЫХ И ПРИКЛАДНЫХ ИССЛЕДОВАНИЙ НАЦИОНАЛЬНОГО ИССЛЕДОВАТЕЛЬСКОГО УНИВЕРСИТЕТА «ТИИИМСХ»

АСТРОНОМИЧЕСКИЙ ИНСТИТУТ АН РУз

КУРБОНОВ НУРИДДИН АБДУРАШИДОВИЧ

ДИНАМИКА ЗАРЯЖЕННЫХ ЧАСТИЦ И ЭНЕРГЕТИЧЕСКИЕ ПРОЦЕССЫ В ОКРЕСТНОСТИ ЗАРЯЖЕННЫХ ЧЕРНЫХ ДЫР

01.03.01- Астрономия
01.03.02- Астрофизика и физика Космоса

АВТОРЕФЕРАТ
ДИССЕРТАЦИИ ДОКТОРА ФИЛОСОФИИ (PhD)
ПО ФИЗИКО –МАТЕМАТИЧЕСКИМ НАУКАМ

Ташкент – 2024

Тема докторской диссертации зарегистрирована в Высшей аттестационной комиссии при Министерстве Высшего Образования, Науки и Инноваций Республики Узбекистан за B2024.2.PhD/FM1082.

Диссертация выполнена в Астрономическом институте имени Улугбека Академии наук Узбекистана.

Автореферат диссертации на трех языках (узбекский, английский, русский (резюме)) размещен на веб-странице Научного совета (https://www.ifar.uz) и на Информационно-образовательном портале «ZiyoNet» (www.ziyonet.uz).

Научный руководитель:	**Тошматов Бобир Абдуманонович** доктор физико-математических наук
	Райимбаев Джавланбек Раджапбаевич доктор физико-математических наук
Официальные оппоненты:	**Атамуротов Фаррух Шухратович** доктор физико-математических наук
	Жураева Нозима Бобомурод кизи доктор философии (PhD) по физико-математическим наукам
Ведущая организация:	**Казахский Национальный Университет имени Аль-Фараби**

Защита диссертации состоится «___» ___ 20__ года в ___ часов на заседании Научного совета DSc.03/31.03.2022.T/FM.10.04 при Институте фундаментальных и прикладных исследований Национального исследовательского университета "ТИИМСХ". (Адрес: 100000, г. Ташкент, улица Кори Ниязова 39, Тел.: +998 71 237-09-61; факс: +998 71 234-09-62; e-mail: info@ifar.uz)

С диссертацией можно ознакомиться в Информационно-ресурсном центре Института фундаментальных и прикладных исследований Национального исследовательского университета "ТИИИМСХ" (зарегистрирована за № ___). (Адрес: 100000, г. Ташкент, улица Кори Ниязова 39, Тел.: +998 71 237-09-61).

Автореферат диссертации разослан « ___ » ___ 20__ года.
(протокол рассылки № ___ от « ___ » ___ 20__ года).

Б.Ж. Ахмедов
Председатель Научного совета по присуждению учёных степеней, д.ф.-м.н., академик

Ш.Н. Мардонов
Учёный секретарь научного совета по присуждению учёных степеней, д.ф.-м.н.

А.Б. Абдикамалов
председатель научного семинара при Научном совете по присуждению учёных степеней, д.ф.-м.н.

ВВЕДЕНИЕ (аннотация диссертации доктора философии PhD)
Актуальность и необходимость темы диссертации.

Изучение заряженных частиц и их динамики в окрестности заряженных черных дыр является весьма актуальной и значимой областью исследований в современной астрофизике и фундаментальной физике. Заряженные черные дыры, описываемые такими решениями, как метрики Рейсснера-Нордстрема и Керра-Ньюмана, предоставляют уникальную лабораторию для изучения взаимодействия гравитационных, электромагнитных и инерционных сил в экстремальных условиях. Эти среды имеют решающее значение для понимания поведения материи и излучения вблизи компактных объектов и для исследования потенциальных отклонений от общей теории относительности, особенно в присутствии сильных электромагнитных полей.

Исследование энергетических процессов, таких как ускорение частиц и генерация высокоэнергетических излучений, имеет глубокие последствия для астрофизических явлений. Многие наблюдаемые явления, включая релятивистские струи, гамма-всплески и высокоэнергетические космические лучи, могут включать механизмы, коренящиеся в динамике заряженных частиц вокруг заряженных черных дыр. Кроме того, эти исследования способствуют нашему пониманию физики плазмы в экстремальных условиях, что необходимо для интерпретации данных с передовых наблюдательных установок, таких как «Event Horizon Telescope» и космических рентгеновских и гамма-телескопов.

Рассматривая эти темы, эта диссертация согласуется с современными усилиями по связыванию теоретических моделей с наблюдениями, продвигая наше понимание среды черных дыр и их энергетических сигнатур. Эта работа не только углубляет понимание высокоэнергетических астрофизических процессов, но и вносит вклад в более широкую цель проверки фундаментальных теорий в экстремальных условиях, что делает ее весьма актуальной как в теоретическом, так и в наблюдательном контексте. В нашей стране также уделяется большое внимание исследованиям механизмов излучения в аккреционном диске ЧД, а также оптических и энергетических процессов вокруг ЧД, а также теоретическим исследованиям теорий гравитации и их проверке на основе наблюдательных данных.

Данная диссертационная работа соответствует задачам, поставленным следующими государственными нормативными документами: Указ Президента Республики Узбекистан № УП-4947 «О Стратегии действий по дальнейшему развитию Республики Узбекистан» от 07.02.2017 г., Постановление Президента Республики Узбекистан № ПП-2789 «О мерах по дальнейшему совершенствованию деятельности Академии наук, организации, управления и финансирования научно-исследовательской деятельности» от 18.02.2017 г.

Актуальность исследования приоритетным направлениям развития науки и технологий Республики Узбекистан.

Диссертация выполнена в соответствии с приоритетными направлениями науки и техники в Республике Узбекистан.

Обзор международных научных исследований по теме диссертации.

Черные дыры в многомерных теориях с дилатонными полями изучил британский физик G.W.Gibbons (Nuclear Physics B, vol. 298). Решения для черных дыр теории EMS исследовали китайские ученые S. Yu, J. Qiu, и C. Gao Classical Quantum Gravity, Volume 38, Number 10).

Первые работы по гравитации Kalb-Ramond были опубликованы M. Kalb и P. Ramond (Physical Review D, vol. 9, no. 8), а решения для черных дыр в этой гравитации опубликованы китайскими учеными Z.-Q. Duan, J.-Y. Zhao, и K. Yang (Eur. Phys. J. C 84, 798).

Энергетические процессы изучались рядом ученых - процесс Пенроуза (Nuovo Cimento Rivista Serie, vol. 1, 1969), магнитный Пенроуз процесс (Mon. Not. R. Astron. Soc, vol. 478) и электрический процесс Пенроуза процесс (Phys. Rev. D, vol. 104, no. 8).

Степень изученности проблемы

В 1969 году известный британский физик (ныне лауреат Нобелевской премии) Роджер Пенроуз предложил механизм, описывающий процесс выделения энергии вращающейся черной дыры. Позднее Н. Дадич предложил механизм выделения энергии, названный «магнитный Пенроуз процесс». В 2021 году Арман Турсунов написал работу, связанную с электрическим процессом Пенроуза. Изучение этих процессов широко проводилось в Европе (Р. Пенроуз, З. Стухлик, М. Колош и др.), в Индии (Н. Дадич, С. М. Ваг, В. Дхурандхар и др.) и учеными других стран мира. В нашей республике теоретическими исследованиями оптических и энергетических процессов вокруг ЧД в различных теориях гравитации потенциально занимались также Б. Ахмедов, А. Абдужаббаров, Д. Райимбаев, А. Турсунов, С. Шайматов и др. Однако в их исследованиях изучение механизма энерговыделения ЧД проводилось в рамках общей теории относительности. В моей диссертационной работе этот процесс рассматривался в альтернативной теории гравитации (черные дыры в теории Эйнштейн-Максвелл-скаляр (EMS) и в гравитации Калб-Рамонда (KR)).

Связь темы диссертации с научно-исследовательскими работами научно-исследовательского учреждения, где выполнена диссертация. Диссертация выполнена в Астрономическом институте имени Улугбека и в рамках научных проектов Института ядерной физики АН РУз: Ф-ФА-2021-510 «Исследования ядерного вещества нейтронных звезд в условиях модифицированной гравитации» (2021-2026).

Цель исследования

заключается в изучении энергетических процессов и движения заряженных частиц вокруг черных дыр.

Задачи исследования:

изучить динамику заряженных частиц вокруг заряженных черных дыр в теории Эйнштейн-Максвелл-скаляр;

исследовать электрический процесс Пенроуза вокруг заряженной черной дыры в гравитации Эйнштейн-Максвелл-скаляр;

изучить процесс Пенроуза в гравитации Калб-Рамонда;

изучить инварианты кривизны, горизонт событий и свойства магнитного поля пространства-времени вокруг регулярной черной дыры.

Объекты исследования представляют собой компактные заряженные релятивистские гравитационные объекты – черные дыры.

Предметы исследования являются электрический Пенроуз процесс в теории Эйнштейн-Максвелл-скаляр и гравитацией Калб-Рамонда.

Методами исследования являются математический аппарат ОТО и численные методы.

Научная новизна исследования заключается в следующем:

впервые показано увеличение интенсивности синхротронного излучения заряженных частиц и эффективности электрического Пенроуз процесса вокруг заряженной черной дыры за счет отрицательных значений безмассового скалярного поля в теории Эйнштейн-Максвелл-скаляр;

впервые показано, что при одинаковых значениях заряда черной дыры эффективность электрического Пенроуз процесса в гравитации Калб-Рамонда выше, чем для черных дыр в ОТО;

впервые в модели Новикова-Торна при рассмотрении намагниченных частиц в аккреционном диске вокруг регулярной черной дыры эффективность энерговыделения превышает эффективность Керровских черных дыр (20%), достигая 22%.

показано, что внутренний радиус аккреционного диска черных дыр одинаков для нелинейной и линейной электродинамики при большом значении параметра намагниченности частиц.

Практические результаты исследования заключаются в следующем:

исследовано синхротронное излучение заряженных частиц вокруг заряженной черной дыры в теории Эйнштейн-Максвелл-скаляр и проведено сравнение интенсивности излучения с черной дырой Рейсснера-Нордстрема;

получены результаты исследования столкновения заряженных частиц и найден критический угловой момент для электрически заряженной черной дыры в гравитации Калб-Рамонда. Показано, что противоположно (относительно заряда черной дыры) заряженные частицы имеют больший критический угловой момент из-за кулоновского взаимодействия;

изучено влияние параметра намагниченности на движение намагниченных частиц в окрестности регулярной черной дыры и найден его экстремум для реалистичной астрофизической системы.

Достоверность результатов исследования обеспечивается следующим:

используются передовые методы общей теории относительности и астрофизики в сочетании с эффективными численными методами и алгоритмами;

теоретические результаты других авторов тщательно проверяются на согласованность;

выводы в высокой степени согласуются с основополагающими принципами полевой теории компактных гравитационных объектов.

Научная и практическая значимость результатов

полученные результаты для заряженной черной дыры в теории Эйнштейн-Максвелл-скаляр могут дать информацию о том, как безмассовое скалярное поле влияет на эффективность выделения энергии черной дырой;

исследование влияния поля Калб-Рамонда на электрический Пенроуз процесс и столкновения частиц вокруг заряженных черных дыр в гравитации Калб-Рамонда может быть полезно при изучении свойств пространства-времени черных дыр в альтернативной теории гравитации;

результаты исследования движения намагниченных частиц и их энергетических процессов вокруг магнитно-заряженных регулярных черных дыр могут быть использованы при изучении аккреционного диска, состоящего из намагниченных частиц, и движения намагниченных нейтронных звезд вокруг центра галактики.

Внедрение результатов исследований

Результаты исследования энергетических процессов и динамики заряженных частиц вокруг заряженных черных дыр в различных теориях гравитации были использованы следующим образом:

результаты по определению круговых орбит для намагниченных и магнитно заряженных частиц вокруг заряженных регулярных черных дыр были использованы несколькими авторами при изучении свойств пространства-времени вокруг черных дыр, а также гравитационных моделей (Physical Review D 108(4), 044030, (2023), European Physical Journal C83(11), 989, (2023), European Physical Journal C 84(2),203, (2024), Physics of the Dark Universe 46,101616, (2024)). Результаты были предоставлены для того, чтобы сделать возможным анализ движения намагниченных и магнитно заряженных частиц вокруг черных дыр на основе теоретических данных для черных дыр;

Результаты изучения энергетических процессов вокруг заряженных черных дыр были использованы рядом авторов при изучении свойств пространства-времени для альтернативной теории гравитации (European Physical Journal Plus 138(7), 635, (2023), Chinese Physics C 48(2), 025101, (2024), European Physical Journal C 84(4), 420, (2024), European Physical Journal C 84(8),829, (2024), European Physical Journal C 84(9),964, (2024)). Результаты используются для анализа круговых орбит заряженных частиц и их энергетических свойств в поле заряженных черных дыр.

Утверждение результатов исследований. Результаты диссертации обсуждались на 1 международной конференции (ICTPA-2024), на 2 республиканских научных конференциях и регулярных еженедельных узбеко-казахстанских семинарах по теоретической физике и астрофизике.

Публикация результатов исследования

Результаты диссертации получены из 7 научных работ, четыре из которых опубликованы в рецензируемых журналах (EPJC Q1, IJMPD Q2).

Объем и структура диссертации

Диссертация содержит 101 страницу и состоит из введения, трех глав, заключения и списка литературы.

Список опубликованных статей Главы диссертации составлены по результатам следующих опубликованных статей:

ЗАКЛЮЧЕНИЕ

По результатам исследований, проведенных в рамках диссертации «Динамика заряженных частиц и энергетические процессы в окрестности заряженных черных дыр», были сделаны следующие выводы:

1. Интенсивность синхротронного излучения, как и эффективность выделения энергии увеличивается с уменьшением значения безмассового скалярного поля в теории Эйнштейн-Максвелл-скаляр;

2. Отдаление точки ионизации понижает эффективность выделения энергии электрического Пенроуз процесса. А увеличение безразмерного параметра l повышает ее. Критический угловой момент уменьшается с увеличением безразмерный параметр l при столкновение заряженных частиц в гравитации Калб-Рамонда;

3. Для регулярной чёрной дыры получена зависимость эффективности энерговыделения аккреционного диска центральной чёрной дыры от её заряда через падающую в неё частицу. Получено, что эффективность увеличивается с ростом заряда ЧД. Показано, что при параметре намагниченности частиц b=10.2 эффективность растет быстрее, чем в модели Керра.

E’LON QILINGAN ISHLAR RO‘YXATI
LIST OF PUBLISHED WORKS
СПИСОК ОПУБЛИКОВАННЫХ РАБОТ

I bo‘lim (part I; I часть)

1. Nuriddin Kurbonov, Javlon Rayimbaev, Mirzabek Alloqulov, Muhammad Zahid, Farrux Abdulxamidov, Ahmadjon Abdujabbarov, Mukhabbat Kurbanova, Charged particles and Penrose process near charged black holes in Einstein-Maxwell-scalar theory // European Physical Journal C, 2023, 83(6), 506, (№ 1. Web of Science: IF=4.2) https://doi.org/10.1140/epjc/s10052-023-11691-9;
2. Muhammad Zahid, Javlon Rayimbaev, Nuriddin Kurbonov, Saidmuhammad Ahmedov, Chao Shen, Ahmadjon Abdujabbarov, Electric Penrose, circular orbits and collisions of charged particles near charged black holes in Kalb-Ramond gravity // European Physical Journal C, 2024. (№ 1. Web of Science: IF=4.3) https://doi.org/10.1140/epjc/s10052-024-13061-5;
3. Javlon Rayimbaev, Nuriddin Kurbonov, Ahmadjon Abdujabbarov, Wen-Biao Han, Dynamics of test particles around magnetically charged regular black holes // International Journal of Modern Physics D, Vol. 31, No. 05, 2250032 (2022), 28 pages (№ 1. Web of Science: IF=1.8) https://doi.org/10.1142/S0218271822500328;
4. Aleksandra Demyanova, Ozodbek Rakhimov, Yunus Turaev, Nuriddin Kurbonov, Javlon Rayimbaev, Characteristic orbits of charged particles around charged black holes». // Proceedings of RAGtime, 2020, 19 pages.

II bo‘lim (part II; II часть)

5. Курбонов Н.А., Демьянова А.Д., «Процесс Пенроуза в пространстве-времени Kerr-Taub-NUT». РИАК-XIII-2020 "Физика фанининг ривожида истеъдодли ёшларнинг ўрни". СЕКЦИЯ-III, стр.169-172;
6. Курбонов Н.А., Демьянова А.Д., «Решение для электрически и магнитно заряженной регулярной черной дыры». РИАК-XIII-2020 "Физика фанининг ривожида истеъдодли ёшларнинг ўрни". СЕКЦИЯ-III, стр.153-156;
7. Н.А.Курбонов, Б.А.Тошматов, «Коллапс пыли в 4D гравитации Эйнштейна-Гаусса-Бонне». «Фан ва таълимни ривожлантиришда ёшларнинг ўрни» 2020, стр 42.

Avtoreferat “IQTISOD-MOLIYA”nashriyotida tahrirdan o‘tkazildi.

Bosishga ruxsat etildi: 05.12.2024 y.
Bichimi: 60x84 1/8 “Times New Roman”
garniturada raqamli bosma usulda bosildi.
Shartli bosma tabog‘i: 3,0. Adadi: 100.Buyurtma: № 169.

“DAVR MATBUOT SAVDO” MCHJ
bosmaxonasida chop etildi.
100198, Toshkent, Qo‘yliq, 4-mavze, 46.