“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

Z.M.BOBUR NOMIDAGI ANDIJON DAVLAT UNIVERSITETI FUNDAMENTAL VA AMALIY TADQIQOTLAR INSTITUTI

ABDULVOXIDOV ALISHER LATIFOVICH

MUQOBIL GRAVITATSIYA NAZARIYALARIDA QORA O‘RALAR ATROFIDA OPTIK-ENERGETIK JARAYONLAR

01.03.01 – Astronomiya
01.03.02 – Kosmos fizikasi va astrofizika

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

Toshkent – 2024

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

Содержание диссертации доктора философии (PhD) по физико-математическим наукам

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KIRISH (PhD dissertatsiyasining annotatsiyasi)

Dissertatsiya mavzusining dolzarbligi. Qora o‘ralar atrofidagi turli astrofizik hodisalarlarga oid matematik modellarni taraqqiyoti va takomillashtirilishi zamonaviy relyativistik (nisbiylik) astrofizikaning eng muhim ustuvor yo‘nalishlaridan biri hisoblanadi. So‘nggi o‘n yil ichida kuzatuv astronomiyasidagi yangi kashfiyotlar ixcham gravitatsiyaviy subyektlar yaqinidagi astrofizik hodisalarlarni tushunish uchun nazariy va matematik asoslarni ishlab chiqishdagi taraqqiyot sur’atini sezilarli darajada tezlashtirdi. Bir vaqtning o‘zida fundamental fizikada yagona nazariyani izlash mavjud umumiy nisbiylik paradigmasidan tashqarida bo‘lgan yangi muqobil energiya nazariyalarini yoki o‘zgartirilgan gravitatsion ramkalarni tadqiqot qilishni taqozo etadi. Bu yangi nazariyalar uchun kritik parametr qiymatlarini aniqlash bilan birga ushbu nazariyalarni kuzatuv va eksperimental ma’lumotlar bilan taqqoslash, astrofizik qora o‘ralar yaqinida sodir bo‘ladigan optik-energetik jarayonlarni matematik simulyatsiya qilish orqali amalga oshiriladi.

Umumiy nisbiylik nazariyasi doirasidagi bir qancha kamchiliklar va nomuvofiqliklarni bartaraf etish uchun muqobil hamda modifikatsiyalangan gravitatsiya nazariyalari zarur. Ushbu nazariyalar umumiy nisbiylik va kvant mexanikasi o‘rtasidagi nomuvofiqliklarni kelishtirish, quyuq materiya va quyuq energiya kabi hodisalarlar uchun tushuntirishlar berish hamda qora o‘ralar kabi ekstremal sharoitlarda gravitatsiya harakati haqida tushuncha berishni maqsad qilgan. Bundan tashqari, muqobil gravitatsiya nazariyalarini o‘rganish fazo-vaqt hamda gravitatsiyaning asosiy mohiyatini chuqurroq tushunishga yordam beradi va bu esa bizning koinot haqidagi tushunchamizdagi yutuqlarga olib keladi. Shunday qilib, astrofizik tadqiqotlarda egri fazoni o‘rganish va tahlil qilish ixcham obyektlarga yaqinlashadi hamda shuning uchun astronomik kuzatishlar natijalari dolzarbdir.

Keyingi yillarda mamlakatimizda fundamental va amaliy tadqiqotlarning dolzarb yo‘nalishlarini rivojlantirishga tobora ko‘proq e’tibor qaratilmoqda. Xususan, istiqbolli yo‘nalishlardan biri bo‘lgan astrofizik tadqiqotlarni rivojlantirish bugungi kunning muhim masalasidir. Mamlakatimizda ilm-fanni muvaffaqiyatli rivojlantirish uchun fundamental tadqiqot va ishlanmalarning asosiy yo‘nalishlari hamda ularni amaliyotda qo‘llash 2022-2026-yillarda O‘zbekiston Respublikasini yanada rivojlantirish bo‘yicha Harakatlar strategiyasida o‘z ifodasini topgan. Shuning uchun, yuqori egrilik gravitatsion nazariyalarida skalarlashtirilgan yechimlarni tadqiq qilish fundamental tadqiqotlar sohasidagi dolzarb masalalardan biri bo‘lib qolmoqda.

Mazkur dissertatsiya ishi quyidagi davlat me’yoriy hujjatlari bilan belgilangan vazifalarga mos keladi: O‘zbekiston Respublikasi Prezidentining 2017-yil 07-fevraldagi “O‘zbekiston Respublikasini yanada rivojlantirish bo‘yicha Harakatlar strategiyasi to‘g‘risida”gi PF-4947-sonli farmoni, O‘zbekiston Respublikasi Prezidentining 2017-yil 18-fevraldagi “Fanlar akademiyasi faoliyatini yanada takomillashtirish, ilmiy-tadqiqot faoliyatini tashkil etish, boshqarish va moliyalashtirish chora-tadbirlari to‘g‘risida”gi PQ-2789-sonli qarori va boshqalar.

Tadqiqotning Respublika fan va texnikasini rivojlantirishning asosiy ustuvor yo‘nalishlariga muvofiqligi. Dissertatsiya tadqiqoti O‘zbekiston Respublikasi fan va

texnikasining ustuvor yo‘nalishlariga muvofiq olib borilgan: II. “Quvvat, energiya va resurslarni tejash”.

Muammoning o‘rganilganlik darajasi. Qora o‘ralar atrofida zarrachalar dinamikasini nazariy tadqiqoti ko‘plab olimlar, jumladan, ingliz (R.Vald, J.Petterson), rus (A.Zaxarov, V.Frolov, I.Novikov), nemis (C.Laemmerzal, J.Kunz, A.Grezenbax), argentinalik (L.Amarilla, E.Eiroa), chexiya (M.Kolos, J.Vrba), hind (N.Dadhich, S.Ghosh, P.Joshi, M.Patil) va boshqalar tomonidan olib borilgan. Biroq torli bulut va kvintessensial mavjudligidagi qora o‘ra atrofidagi magnit zarrachalarning harakati to‘liq o‘rganilmagan. Bundan tashqari, zarrachalarning doiraviy orbitalarini va akkretsiya disklari uchun nazariy model yaratish haqida ham hech qanday tadqiqot yo‘q.

Zarrachalar harakatining nazariy va astrofizik modellari Respublika olimlar B.J.Ahmedov, A.A.Abdujabborov, A.A.Tursunov, G‘arblik olimlardan R.Wald, S.R.F.Felice, F.Sorge va boshqalar tomonidan umimiy nisbiylik nazariyasi doirasida ishlab chiqilgan. Biroq markaziy obyekt torli bulut va kvintessensial bilan o‘ralgan bo‘lsa, naraiy bilimlarni takomillashtirish masalasi ochiqligicha qolmoqda.

Oddiy qora o‘ra atrofidagi astrofizik jarayonlarga qorong‘i materiyaning ta’siri ham o‘rganilmagan. Bunday obyektlar atrofidagi magnitlangan zarrachalar dinamikasini tavsiflovchi nazariy modellarni ishlab chiqishga yordam beradi.

Dissertatsiya mavzusini dissertatsiya olib borilayotgan oliy o‘quv yurtlari va ilmiy tadqiqot muassasalarining ilmiy ishlari bilan bog‘lash. Dissertatsiya Innovatsion rivojlanish vazirligi tomonidan moliyalashtirilgan ilmiy loyihalar doirasida bajarilgan. F-FA-2021-510 “Modifikatsiyalashtirilgan gravitatsiya sharoitida neytron yulduzlarining yadroviy moddasini tekshirish”.

Tadqiqot maqsadi turli gravitatsiya modellarida qora o‘ralar yaqinidagi zarralar va kvazi davriy tebranishlar dinamikasini tavsiflash uchun astrofizik modellarni ishlab chiqish hamda takomillashtirishdan iborat.

Tadqiqot vazifasi:

Torli bulut va kvintessensial maydon mavjudligida Shvartsshild qora o‘raining atrofida sinov zarralarining harakatini o‘rganish;

Torli bulut va kvintessensial parametrlarning hodisalar gorizonti radiusiga ta’sirini tadqiq etish;

torli bulutining turli qiymatlari va kvintessensial parametrlarining samarali imkoniyatlarini tahlil qilish;

torli bulut va kvintessensial maydon mavjudligida aylana orbitalariga mos keladigan zarrachalar energiyasi hamda burchak impulslarini o‘rganish;

eng ichki barqaror dumaloq orbitalarning radiusini torli bulut va kvintessensial parametrlar funksiyasi sifatida tahlil qilish;

barqaror aylana orbitalarida tebranish traektoriyalarini o‘rganish;

Kepler chastotasini o‘rganish va uni relyativistik presessiya modelida egizak tepalik QPO tahliliga qo‘llash;

mikrokvazarlardagi qora o‘ra massasining cheklovchi qiymatlarini olish;

qora o‘ra atrofidagi burilish burchagini T-duallikdan nol nuqta uzunlik parametriga nisbatan o‘rganish;

Eynshteyn-Eyler-Heisenberg qora o‘ralari uchun plazma bo‘lmagan va plazma

muhitida burilish burchaklarini tahlil qilish.

Tadqiqot obyekti bu astrofizik qora o‘ralar, nol va nolga teng bo‘lmagan qolgan massa sinov zarralari, kvintessens quyuq materiya.

Tadqiqot predmeti – ixcham gravitatsion obyektlar yaqinidagi sinov zarralari dinamikasini o‘rganish uchun astrofizik modellar, differensial tenglamalarni yechishning raqamli va analitik usullari.

Tadqiqot usullari hisoblash matematikasi usullari, nazariy astrofizika usullari, matematik fizikaning zamonaviy usullari, maydon va zarrachalar harakati uchun differensial tenglamalarni hisoblashning analitik hamda raqamli usullaridan iborat.

Tadqiqotning ilmiy yangiligi quyidagilardan iborat:

Ma’lum bo‘lishicha, torli bulutning mavjudligi hodisalar (yoki kosmologik) gorizontning biroz o‘sishiga (yoki kamayishiga) sabab bo‘ladi va kvintessensial maydon hodisalar gorizontining biroz oshishiga olib keladi, kosmologik esa yetarli darajada kamayadi.

Hodisalar gorizontining mavjudligi/yo‘qligiga ikkita maydon parametrlarining mos keladigan qiymatlari, shuningdek, maydonlar ta’sirining hodisalar gorizonti radiusiga ta’siri tahlil qilindi. Hodisalar gorizonti torli bulutlar mavjudligida ortib borishi uchun olinadi, kvintessensial parametrning oshishi bilan esa u kamayadi.

Torli bulutlarning turli qiymatlari va kvintessensial parametrlarining samarali potentsialini tahlil qilish shuni ko‘rsatdiki, ikkala parametrning oshishi samarali potensialning pasayishiga olib keladi.

Zarrachalar energiyasi va aylana orbitalariga mos keladigan burchak impulslarini o‘rganish shuni ko‘rsatdiki, torli bulut parametri qiymatlari uchun burchak impulsi ortadi, kvintessensial maydon mavjud bo‘lganda esa impuls kamayadi.

Kvintessensial parametrning turli qiymatlari uchun torli bulut parametriga bog‘liq bo‘lgan eng ichki barqaror aylana orbitalari (IBAO) radiusi tahlillari shuni ko‘rsatdiki, IBAO radiusi oshgani sayin zarrachalarning energiyasi (burchak impulsi) kamayadi (yoki ortadi).

Energiya samaradorligi torli bulut parametrlarining oshishi bilan ortib borishi va kvintessensial maydon yo‘qligida 70 %gacha yetishi ko‘rsatilgan.

Torli bulutlar va kvintessensial parametrlar mavjud bo‘lganda, tebranish traektoriyalari kuzatiladi va ikkala parametrning birgalikda ta’siri natijasida barqaror aylana orbitalari paydo bo‘ladi, trayektoriyalar barqaror va chegaralangan bo‘ladi.

Aniqlanishicha, Kepler chastotasi kvintessensial maydon ishtirokida biroz masofaga boradi va kvintessensial parametr ortishi bilan masofa kamayadi.

Tadqiqotning amaliy natijalari quyidagilardan iborat:

Kuzatilgan QPO ma’lumotlaridan foydalangan holda torli bulutlar parametri mavjud bo‘lganda, GRS 1915+105, GRO J1655-40 va Sgr A* mikrokvazarlarida qora o‘ra massasining cheklovchi qiymatlari birinchi marta quyidagicha olingan:

GRO J1655-40 taxminan 8,4-18,4 $M_{\odot}$, GRS 1905+105 ning massasi 23,6-23,9 $M_{\odot}$ va Sgr A* ning massasi 3,8-4,02 $M_{\odot}$.

Qora o‘ra atrofidagi fotonlarning burilish burchagini T-ikkilanishidan nol nuqta uzunlik parametri bo‘yicha tahlil qilish shuni ko‘rsatdiki, nol nuqta uzunlik parametri ortganda burchak juda sekin tezlikda kamayadi.

Uzunlik parametrining nolinchi nuqtasi ortib borishi bilan burilish burchagi sekin tezlik bilan kamayib borishi va bir xil plazma holatida bu qiymat bir xil bo‘lmagan plazmanikiga qaraganda ancha yuqori nuqtaga ega bo‘lishi aniqlandi.

Eyler-Gayzenberg parametrining ortishi bilan radial va tangensial chastotalar kamayishi, zaryadning ortishi bilan esa ko‘payishi ko‘rsatilgan. Bundan tashqari, Relyativistik Presessiya modeli uchun yuqori va pastki chastotalar Eyler-Heisenberg parametrini oshirish uchun ortadi hamda zaryad parametrini oshirish uchun pasayadi.

Tadqiqot natijalarining ishonchliligi matematik fizika, hisoblash matematikasi va relyativistik astrofizikaning zamonaviy tasdiqlangan usullarini qo‘llash orqali ta’minlanadi. Natijalar qat’iy ravishda umumiy nisbiylik va nazariy fizikaning matematik apparati doirasida olingan. Hisoblashning zamonaviy raqamli va analitik usullari ham qo‘llaniladi hamda natijalar mavjud kuzatuv ma’lumotlari va boshqa mualliflarning natijalari bilan taqqoslanadi. Tezisning tuzilgan xulosalari ixcham obyektlar astrofizikasining asosiy qoidalariga mos keladi.

Tadqiqot natijalarining ilmiy va amaliy ahamiyati. Tadqiqot natijalarining ilmiy ahamiyati shundaki, turli gravitatsiya modellarida qora o‘ralar uchun yechimlarni tahlil qilish gravitatsiyaning turli nazariy modellarini o‘rganish uchun foydali vosita bo‘lishi mumkin.

Tadqiqot natijalarining amaliy ahamiyati qora o‘raning dinamik va statsionar fazo-vaqt cheklovlarini qurishda egizak tepalik QPOs kuzatishlari bilan ular rol o‘ynashi mumkin

Tadqiqot natijalarini qo‘llash. O‘zgartirilgan tortishish nazariyasida zaryadlangan va magnitlangan zarrachalar dinamikasining ishlab chiqilgan matematik modellari asosida quyidagilar ishlab chiqilgan:

magnitlangan zarrachalar harakati va magnit effektlar bo‘yicha olingan ilmiy natijalar Shanxaydagi Fudan universiteti (FU) olimlari tomonidan qo‘llanilgan (FU, Xitoy, 2024-yil 16-may ma’lumotnomasi);

zarrachalarning magnit qiymati va deformatsiyalangan fazoning bunday zarrachalar orbitalariga ta’siri hisoblangan. Foton orbitalari bo‘yicha natijalar xorijiy tadqiqotchilarning ishlarida, yuqori impakt faktorli xorijiy jurnallarda qo‘llanilgan (Physical Review D, 2024; taqdim etilgan; European Physical Journal C, 2024, taqdim etilgan) tavsiflash uchun 3 ta nashr etilgan ilmiy maqolalarda foydalanilgan.

Natijada, aylanuvchi qora tuynuk atrofida magnitlangan zarrachalarning ta’siri, o‘zgartirilgan tortishish nazariyalari doirasida ixcham obyektlar atrofida magnitlangan zarrachalar dinamikasi haqida ma’lumot olish mumkin.

Tadqiqot natijalarini sinovdan o‘tkazish. Tadqiqot natijalari 1 ta xalqaro konferensiya va 3 ta mahalliy ilmiy konferensiyalarda ma’ruza qilindi hamda muhokama qilindi.

Tadqiqot natijalarini nashr etish. Tadqiqot natijalari bo‘yicha 6 ta ilmiy maqola chop etilgan, ulardan 3 tasi O‘zbekiston Respublikasi Oliy ta’lim, fan va innovatsiyalar vazirligi huzuridagi Oliy attestatsiya komissiyasi tomonidan tavsiya etilgan xalqaro ilmiy jurnallarda chop etilgan.

Dissertatsiyaning hajmi va tuzilishi. Dissertatsiya kirish, to‘rt bob, xulosa va foydalanilgan adabiyotlardan tashkil topgan, hammasi 82 betdan iborat.

DISSERTATSIYANING ASOSIY MAZMUNI

Dissertatsiyaning kirish qismida mavzuning dolzarbligi va zarurligini, tadqiqotning respublika fan va texnikasi rivojlanishining ustuvor yo‘nalishlariga muvofiqligini, muammoni bilish darajasi, uning oliy o‘quv yurtlarining ilmiy-tadqiqot rejalari bilan bog‘liqligini hamda dissertatsiya bajarilgan ta’lim muassasasi hamda tadqiqot maqsadi, vazifalari, tadqiqot obyekti, fan haqida qisqacha ma’lumot, metodlar, ilmiy yangilik, amaliy natija, ishonchlilik, natijalarning ilmiy va amaliy ahamiyati, natijalarni amaliyotga joriy etish, natijalarni tasdiqlash, natijalarni nashr etish, shuningdek, dissertatsiyaning tuzilishi va hajmini ko‘rsatadi.

Birinchi bob “Adabiyotni ko'rib chiqish” deb nomlangan hamda unda zarrachalar dinamikasi sohasidagi tadqiqotlar va turli gravitatsiya modellarida qora o‘ralarning turli yechimlari, shu jumladan, Kiselev qora o‘ralari yechimlari, T-ikkilanishi va Eynshteyn-Eyler-Geyzenberg modelidagi o‘ralar yo‘qligi haqida umumiy ma’lumot berilgan. Ushbu bobda umumiy nisbiylik yoki muqobil gravitatsiyaning nazariyalari doirasida daviy bo‘lmagan (kvazperiodik) tebranish (DBT) modellari bo‘yicha tadqiqotlarni ko‘rib chiqish ham muhokama qilingan.

Ikkinchi bob “Sinov zarralari va torli bulutli Kiselev qora o‘raning atrofidagi davriy bo‘lmagan tebranishlar” deb nomlangan hamda bu bob kvintessensiya bilan o‘ralgan va skalyar torli bulut maydoniga botgan Shvartsshild qora o‘rasi atrofidagi sinov zarralari dinamikasini o‘rganishga bag‘ishlangan. Biz tadqiqotimizni quyuq energiya uchun holat tenglamasi parametrining belgilangan qiymatlari uchun qora o‘ra gorizontining mavjudligiga mos keladigan kvintessensiya va torli bulut parametrlariga mos bo‘lgan qiymatlarini aniqlashdan boshlaymiz. Shuningdek, biz sinov zarralarining aylana harakati uchun samarali potensialning xatti-harakatlarini, energiya va zarrachalarning burchak impulsini ichki barqaror aylana orbitalari (IBAO) bilan birga o‘rganamiz.

Biz zarrachalarning barqaror aylana orbitalari bo‘ylab tebranishlaridagi asosiy chastotalarni o‘rganamiz. Biz orbitalarning barqarorligini Lyapunov ko‘rsatkichi bilan bog‘ladik va tartibsiz xatti-harakatlar grafik tarzda o‘rganiladi. Nihoyat, biz davriy bo‘lmagan tebranishlarni (DBT) tavsiflash uchun asosiy chastotalarni qo‘llaymiz va ikkala maydon mavjud bo‘lganda past chastotali egizak tepalik DBT kuzatilmaydi. Shuningdek, biz GRO J1655-40 & GRS 1915+105 mikrokvazarlari va Somon yo‘li galaktikasi markazida joylashgan qora o‘ra nomzodlarining torli bulutlari parametri hamda massasi uchun cheklash qiymatlarini olamiz. Umuman olganda, DBT ni o‘rganishda qo‘llash maqsadida torli bulut bilan o‘ralgan kvintessensial qora o‘ra atrofida sinov zarralari dinamikasi tahlili o‘tkazildi.

Kvintessensiya va torli bulut bilan bog‘liq bo‘lgan statik va sharsimon simmetrik qora o‘ra $x^{\mu} = (t, r, \theta, \varphi)$ yechimi sharsimon koordinatalarda quyidagi chiziq elementi bilan tasvirlangan.

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

metrika funksiyasi bilan

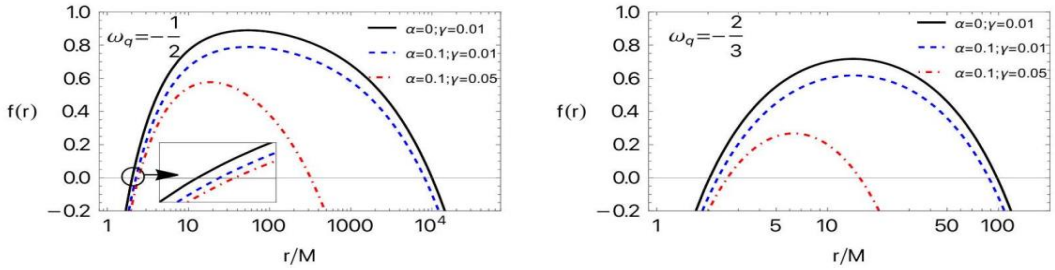
$$f(r) = 1 - \alpha - \frac{2M}{r} - \frac{\gamma}{r^{3\omega_q+1}} \qquad (2)$$

bu yerda M qora o‘raning umumiy massasi hisoblanadi.

Materiya/energiyaning mukammal suyuqlik taqsimoti uchun EoS parametri -$-1 < \omega_q < -\frac{1}{3}$ oralig‘idagi qiymatni oladi va $\omega_q = -1$ bo‘lganda u kosmologik doimiylikni tiklaydi. Shuning uchun, test qiymatlari sifatida, ushbu maqola davomida biz $\omega_q = -\frac{1}{2}$va $\omega_q = -\frac{2}{3}$ holatlarini ham ko‘rib chiqamiz.

$$f(r) = 1 - \alpha - \frac{2M}{r} - \begin{cases} \gamma r^{\frac{1}{2}}, & \omega_q = -\frac{1}{2} \\ \gamma r, & \omega_q = -\frac{2}{3} \end{cases} \tag{3}$$

Umuman olganda, sharsimon simmetrik qora o‘raning hodisalar gorizonti radiusini $g^{rr} = 0$ bilan aniqlash mumkin.



1-rasm. γ va ω_q ning turli qiymatlari uchun hodisalar gorizonti radiusining α torli bulutlariga bog‘liqligi.

1-rasmda $f(r)$metrik funktsiyaning a va g ning turli qiymatlari uchun radial bog‘liqligi ko‘rsatilgan: $\omega_q = -\frac{1}{2}$ va $-\frac{2}{3}$. Ikkala paneldan ham ko‘rish mumkinki, chiziqlar nolni ikki xil masofada kesib o‘tadi (metrik funksiya nol qiymatni qabul qiladi), hodisalar va kosmologik gorizontlarni (kvintessensial maydon tufayli) ifodalaydi. Ikkala torli bulutlari va kvintessensial maydon mavjud bo‘lganda, gorizontlar bir-biriga yaqinlashadi. Bundan tashqari, kosmologik gorizontning radiusi juda sezgir ekanligi ham ko‘rinib turibdi.

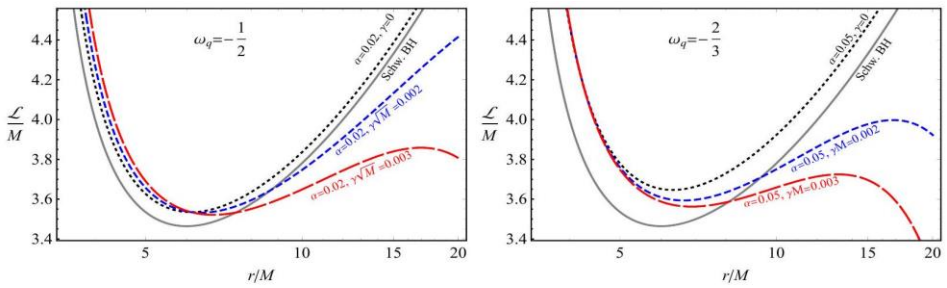
Biz barqaror dumaloq orbitalarni tadqiq qildik. Sharsimon nosimmetrik qora o‘ra atrofida sinov zarrasining bunday orbitalarini quyidagi shartlar aniqlaydi:

$$V_{\text{eff}} = \mathcal{E},\ V'_{\text{eff}} = 0. \tag{4}$$

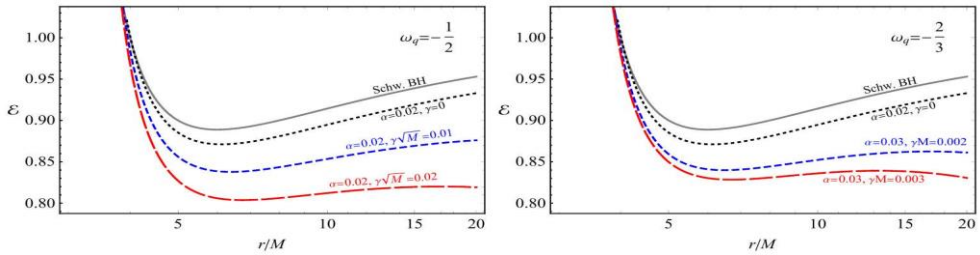
Dumaloq orbitalarga mos keladigan sinov zarralarining burchak momentumi va energiyasi uchun ifodalar quyidagi shaklni oladi:

$$\mathcal{L}^2 = -\frac{r^2\left(\gamma + 2Mr^{3\omega_q} + 3\gamma\omega_q\right)}{2(3M + (\alpha-1)r)r^{3\omega_q} + 3\gamma\left(\omega_q + 1\right)} \tag{5}$$

$$\mathcal{E}^2 = -\frac{2r^{-3\omega_q - 1}(\gamma + (2M + (\alpha-1)r)r^{3\omega_q})^2}{2(3M + (\alpha-1)r)r^{3\omega_q} + 3\gamma\left(\omega_q + 1\right)} \tag{6}$$



2-rasm. α, γ va ω_q. parametrlarining turli qiymatlari uchun radial koordinatalarga bog‘liq holda aylana orbitalardagi sinov zarrachalarining burchak impulsi.



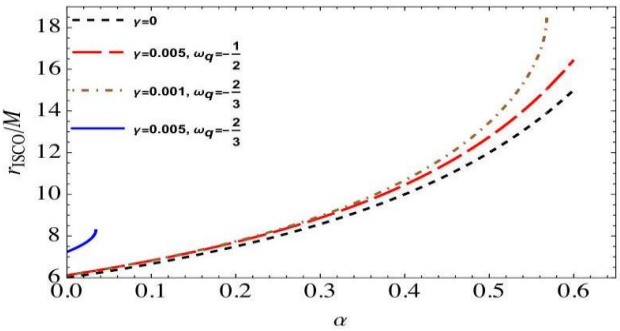
3-rasm. α, γ va ω_q ning turli qiymatlari uchun radial koordinata funksiyasi sifatida qora o‘ra atrofida aylana orbitalarida sinov zarralarining energiyasi.

2-rasmda torli bulutlardagi Shvartsshild qora o‘ralari atrofidagi dumaloq orbitalarga mos keladigan sinov zarralarining burchak impulsini radial bog‘liqligi va fazo-vaqt parametrlarining turli qiymatlari uchun kvintessensial maydon ko‘rsatilgan. Rasmdan ko‘rinib turibdiki, torli bulutlar mavjud bo‘lganda burchak impulsining qiymati ortadi, kvintessensial maydonning mavjudligi esa uning pasayishiga olib keladi. Shuni ta’kidlash mumkinki, γ ning ta’siri kattaroq masofalarda dominant bo‘lib, quyuq materiyaga ta’sir qiladi.

Kattaroq masofalarda burchak impulsida maksimallik bo‘ladi va ikkala kvintessensial maydon parametrlarining ortishi tufayli maksimal pasayadi hamda markaziy qora o‘ra tomon siljiydi. 3-rasmda α, γ va ω_q parametrlarining turli qiymatlari uchun torli bulutlarda kvintessens qora o‘ra atrofida aylana orbitalariga mos keladigan sinov zarrachalari energiyasining radial bog‘liqligi ko‘rsatilgan. Eng ichki barqaror aylana orbita (IBAO) $\partial_{rr}V_{\text{eff}}(r_{\text{ISCO}}) = 0$ va/yoki $\partial_r \mathcal{L} = 0$ sharti (4) bilan birga qondirishi kerak. IBAO radiusi uchun mos keladigan tenglama quyidagi shaklni oladi:

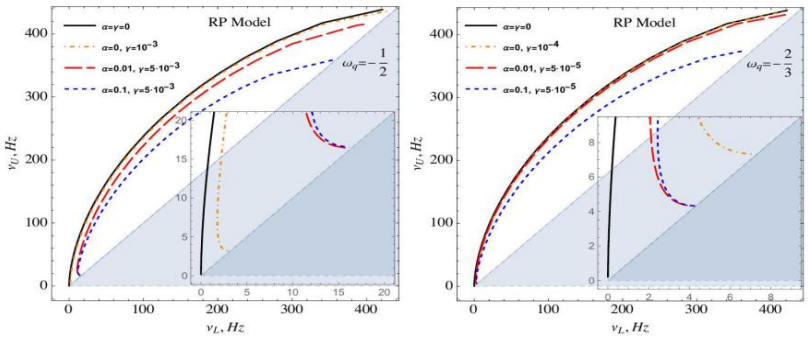
$$\gamma 6M\left[\omega_q\left(3\omega_q - 4\right) - 2\right] + (\alpha - 1)r_{\text{ISCO}}\left(9\omega_q^2 - 1\right)\Big\}$$
$$- \frac{2M}{r_{\text{ISCO}}^{-3\omega_q}}\left[6M + (\alpha - 1)r_{\text{ISCO}}\right] - \frac{3\gamma^2}{r_{\text{ISCO}}^{3\omega_q}}\left(\omega_q + 1\right)\left(3\omega_q + 1\right) = 0. \qquad (7)$$

Tenglamadan (7) osongina ko‘rish mumkinki, Shvartsshild holatida agar $\alpha = \gamma = 0$ bo‘lganda IBAO radiusi $r_{ISCO} = 6M$ bo‘ladi. Biroq tenglama analitik tarzda hal qilinishga juda murakkablik qiladi. Shuning uchun biz kvintessensial va torli bulut parametrlarining o‘zgarishiga nisbatan IBAO (ichki barqaror aylana orbita // innermost stable circular orbit (ISCO)) radiusi harakatining grafik tahlillarini taqdim etamiz. IBAO radiusi α parametrining funktsiyasi sifatida kvintessensiya parametrlarining turli qiymatlari uchun 4-rasmda ko‘rsatilgan. Ko‘rinib turibdiki, IBAO ham torli bulutlar, ham kvintessensial maydon mavjudligida kengayadi.



4-rasm. IBAO radiusi γ va ω_q ning turli holatlari uchun α parametrining funksiyasi sifatida.

Qora o‘ra (black hole (BH)) atrofidagi zaryadlangan sinov zarralarining dinamikasi zarralarning radial va burchak yo‘nalishdagi kvazigarmonik tebranishlariga asoslangan QPO larning mavjudligini tushuntiradi. Biz relyativistik jarayon (RJ) modelida egizak tepalikli QPO larning yuqori va pastki chastotalarini ko‘rib chiqamiz. RJ modeli yuqori va pastki chastotalarni radial, vertikal va orbital tebranishlar chastotalari bilan $\nu_U = \nu_\phi \& \nu_L = \nu_\phi - \nu_r$ sifatida belgilaydi.



5-rasm. Turli α, γ, va ω_q uchun torli bulutli Kiselev qora o‘rasining atrofidagi yuqori va quyi chastotalar o‘rtasidagi bog‘liqlik. Bu erda biz $M = 10M_\odot$ ni tanladik.

5-rasmda biz relativistik presessiya modelida kvintessensial maydon va torli bulutlar mavjudligida qora o‘ra atrofidagi egizak tepalik QPO larning yuqori hamda pastki chastotalari diagrammasini ko‘rsatdik. $\nu_U - \nu_L$ uchun diagrammadagi egri chiziqlar $\omega_q = -1/2$ va $-2/3$ holatlarida Shvartsshild holati bilan taqqoslanadi va $\omega_q = -1/2$ da $\gamma = 10^{-3}$ ga ega kvintessensial maydon mavjudligi QPO yuqori chastotali chastotalarni biroz pasayishiga olib kelishi aniqlandi. Bundan tashqari $\alpha = 0.01$ bo‘lgan torli bulut mavjud bo‘lganda taxminan 5 Hz dan past bo‘lgan past chastotali QPOlar kuzatilmaydi va u taxminan 20 Hz gacha siljiydi. Biroq $\omega_= -\frac{2}{3}$ da γ ning minimal yuqori va pastki chastotalarga ta’siri α ga qaraganda kuchliroq kuzatilishi mumkin. Bundan tashqari, α ning ortishi bilan yuqori chastotali QPO larning yuqori va pastki chastotalari ω_q. ning ikkala qiymati uchun yetarli darajada kamayishi ko‘rinadi.

“Plazmadagi T-ikkilanishdan qora o‘raning zaif gravitatsiya linzalari” deb nomlangan uchinchi bob T-ikkilanishi nuqtai nazaridan plazma muhitining qora o‘ra atrofidagi zaif gravitatsiya linzalariga ta’sirini o‘rganishga bag‘ishlangan. Natijalarimiz shuni ko‘rsatdiki, qora o‘ra atrofidagi yorug‘lik nurlarining burilish burchagiga l_0 parametri sezilarli darajada ta’sir qiladi, uning ortishi burilish burchagining pasayishiga olib keladi, plazmaning burilish burchagiga ta’siri esa aksincha natija ko‘rsatadi.

Shuningdek, biz plazma taqsimotining har xil turlarini, jumladan, bir xil ω_e =const, Birlik Izotermik Sfera muhiti va Birlik Bo‘lmagan Izotermik gaz sferasi plazmasini ko‘rib chiqamiz. Biz qora o‘ra atrofida plazma mavjudligida T-ikkilanishga tegishli l_0 parametrining ta’sirini hisobga olgan holda, gravitatsiya kuchsiz linzalari tufayli tasvir manbaining umumiy kattalashishini tahlil qildik.

Bu erda biz sharsimon simmetrik qora tuynuk (BH) yechimi atrofida gravitatsiya linzalari uchun zaif linzalash rasmiyatchiligini qo‘llashni rejalashtirmoqdamiz.

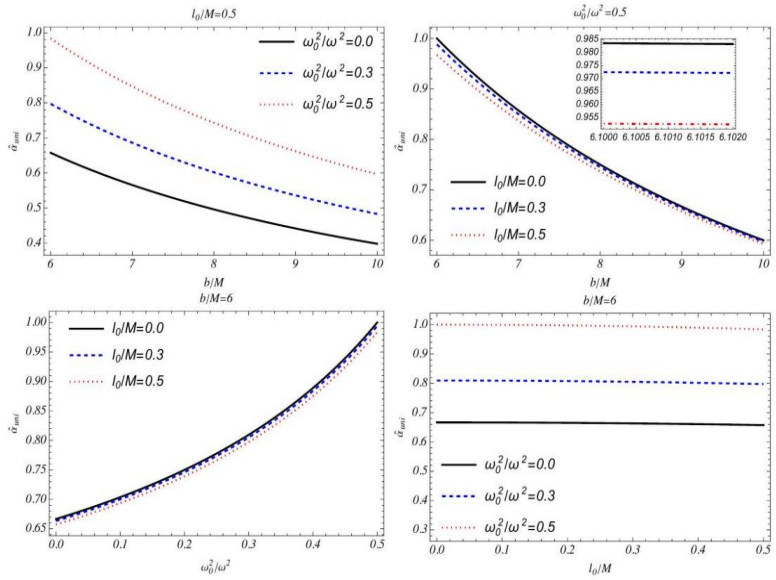
$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2), \tag{8}$$

bilan

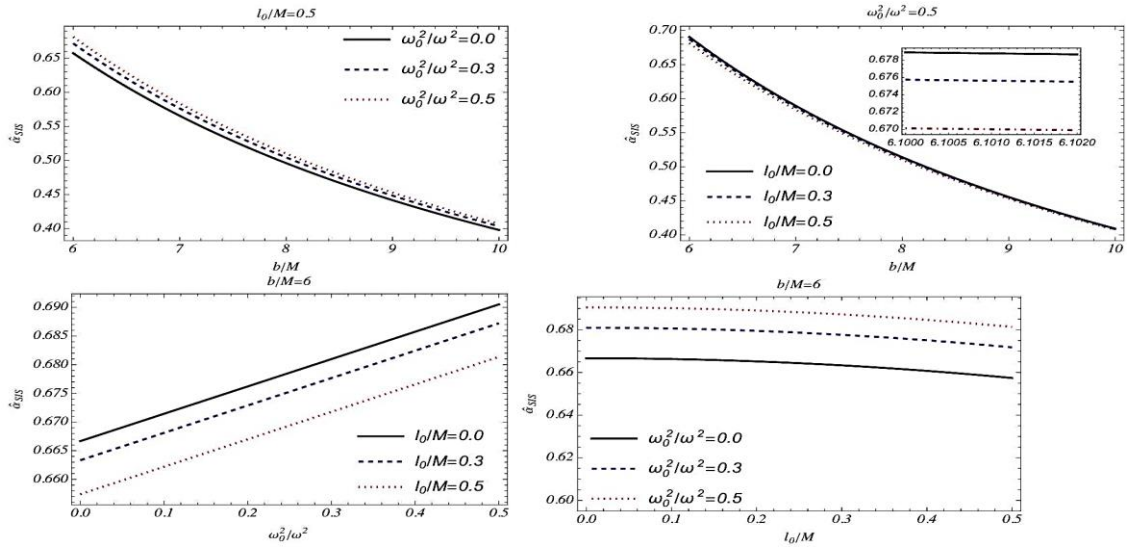
$$f(r) = 1 - \frac{2Mr^2}{\sqrt{(l_0^2+r^2)^3}} \tag{9}$$

Bu yerda l_0 T-ikkilanishdan fazo vaqtning nol nuqtasi uzunligi, M qora o‘ra massasi. Biz zaif maydon rejimini ko‘rib chiqamiz.

l_0 va ω_0/ω qiymatlarining keng diapazoni uchun 6-rasmda yorug‘lik nurlarining qora tuynuk atrofidagi burilish burchagi ta’sir parametri b funksiyasi sifatida ifodalanadi. Burilish burchagining plazma chastotasi ω_0/ω va T-ikkilanish parametri l_0 ta’sir parametrining qat’iy qiymatlari uchun bog‘liqligi 6-rasmning pastki qismidagi boshqa ikkita chizmada ko‘rsatilgan. Ushbu grafiklar shuni ko‘rsatadiki, plazma muhiti xususiyatlarining mavjudligi Qora o‘ra atrofida yorug‘lik nurlarining burilish burchagining egilishiga olib keladi. Bundan tashqari, belgilangan chastota uchun l_0 parametri oshirilganda yorug‘lik nurlarining egilish burchagi deyarli o‘zgarmaydi. Aksincha, plazma chastotasining ko‘tarilishi bilan burilish burchagi qiymati T-ikkilanish l_0 parametrining turli qiymatlarida bir xil tarzda asta-sekin o‘sib borishini namoyish etadi. Ta’sir parametri b ortib borishi bilan gravitatsiya burilish burchagi nolga yaqinlashadi.



6-rasm. Burilish burchagi $\hat{\alpha}_{uni}$ ning ta’sir parametri b ga bog‘liqligi, l_0 parametri l_0/M parametrining turli qiymatlari va plazma muhiti ω_e^2/ω^2 ga bog‘liqligi. Amaldagi mos keladigan parametr b = 6.



7-rasm. l_0 parametrining turli qiymatlari va plazma muhiti ω_c^2/ω^2. uchun b ta'sir parametri, l_0/M parametrining $\hat{\alpha}_{SIS}$ burilish burchagiga ta'siri. Bog'langan sobit parametr b/M=6.

7-rasmning yuqori panellari l_0 parametrining sobit qiymatlari va plazma chastotasi hamda foton chastotasi ω_c/ω nisbati uchun burilish burchagining ta'sir parametri b ga bog'liqligini ko'rsatadigan ikki xil chizmaga mos keladi. Ushbu chizmalardan osongina ko'rish mumkinki, gravitatsiya burilish burchagi ta'sir parametri b ko'tarilishi bilan nolga intiladi. 7-rasmning pastki panellari burilish burchagining qiymati plazma chastotasining bir xil bo'lmagan plazma holatida ω_c/ω o'zgarishiga va T-ikkilikdan l_0 parametriga bog'liqligini ko'rsatadi. Pastki o'ng rasm yorug'lik nurlarining egilish burchagi l_0 parametri ta'sirida bir oz pasayishini va bir xil bo'lmagan plazma muhiti ta'sirida chap grafikdan aksincha ekanligini ko'rsatadi.

"Eynshteyn-Eyler-Geyzenberg qora o'rasining zaif gravitatsiya linzalari va asosiy chastotalari" deb nomlangan to'rtinchi bob Eynshteyn-Eyler-Geyzenberg (EEH) qora o'rasida gravitatsiya kuchsiz linzalari hamda asosiy chastotalarni tahlil qilishga bag'ishlangan. Biz zaif maydon chegaralarida EEH qora o'ra tomonidan yorug'likning burilish burchagini hisoblaymiz. Bu yorug'likning egilishi global va topologik effekt ekanligini anglatadi. Buning uchun biz Gauss egriligini chiqaramiz va Gauss-Bonnet teoremasini (GBT) qo'llaymiz. Bundan tashqari, biz yorug'likning plazma muhiti tomonidan burilish burchagini aniqlaymiz. Shuningdek, biz EEH qora o'rasining vakuum va plazma muhitida grafik tarzda qanday harakat qilishini ko'rib chiqamiz. Bundan tashqari, biz EEH qora o'ralarining uch xil modeli bilan asosiy chastotalarni o'rganamiz.

Statik va sharsimon elektr zaryadlangan shaklda EEH qora o'rasi ko'rsatkichi:

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (10)$$

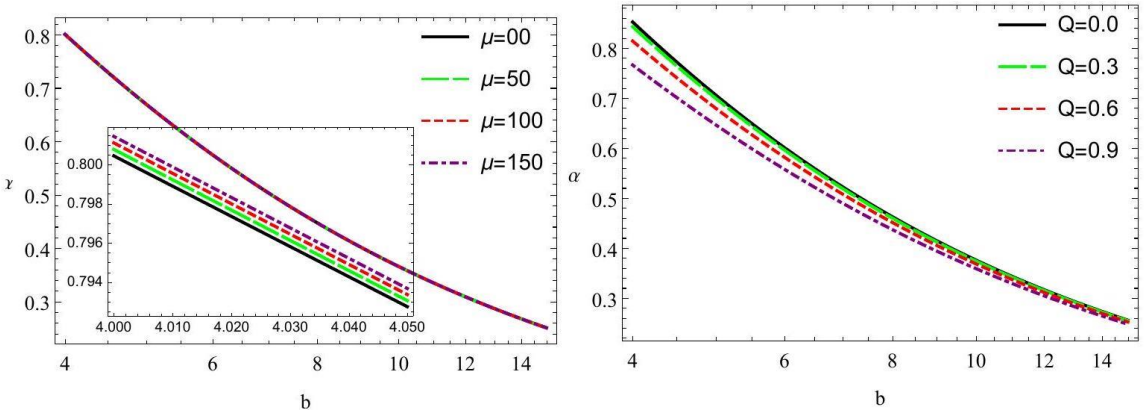
Elektr maydoni uchun $f(r)$ metrik holati quyidagicha aniqlanadi

$$f(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - \frac{\mu Q^4}{20r^6} \quad (11)$$

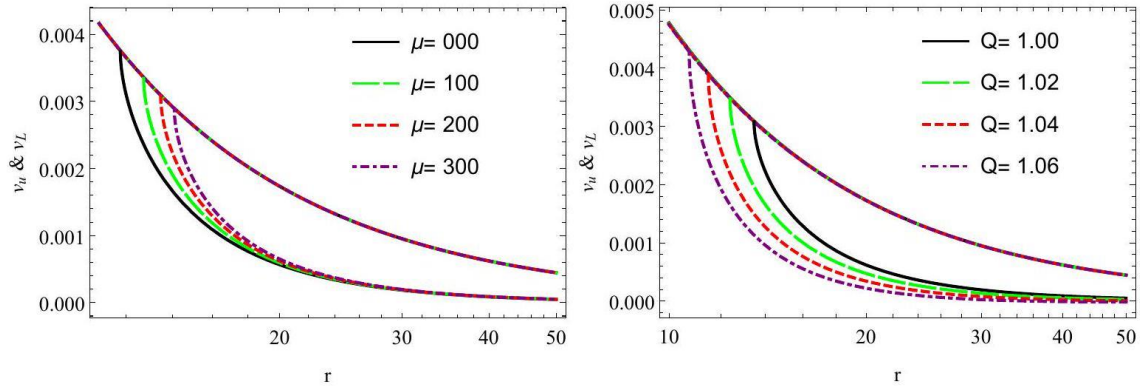
bu yerda M, Q va μ mos ravishda Qora o'ra, elektr zaryadi va EylerGeyzenberg parametrining massasini ifodalaydi.

8-rasmda chap hamda o'ng panelda mos ravishda μ va Q qiymatlarini o'zgartirish

uchun burilish burchagi α ning ta’sir parametriga nisbatan b harakati ko‘rsatilgan. Chap chizmada $M = 1, Q = 0.7$ va μ parametrning turli qiymatlari uchun: $\mu = 0,50,100,150$. ni olamiz. μ ning yuqori qiymatlari uchun burilish burchagi μ ning kichik qiymatlari uchun $4 \leq b \leq 15$ ta’sir parametri uchun ortadi va kamayadi, deb tahlil qilamiz. To‘g‘ri chizmada EEH qora o‘rada qo‘zg‘almas $M = 1$ va $\mu = 50$ uchun $Q = 0,0.3,0.6,0.9$ ni ko‘rib chiqamiz. Q ning katta qiymatlari uchun asta-sekin kamayib boruvchi burilish burchagi harakatini olamiz. Biz chizmalar uchun qora o‘raning domenini $4 \leq b \leq 15$ deb olamiz.



8-rasm. Vakuum holati uchun μ (chap grafik) va Q (o‘ng grafik) ning o‘zgaruvchan qiymatlari uchun burilish burchagi α qarshi ta’sir parametri b.



9-rasm. RP modeli: $= 1, Q = 1, \mu = 200$ o‘zgarmas qiymatlar uchun radial koordinata r bo‘ylab v_u&v_L chastotalari, bu erda o‘zgaruvchan qiymatlar chizma yozuvida ko‘rsatilgan.

Standart relyativistik presessiya (RP) modeli yuqori hamda pastki chastotalarni mos ravishda $v_U = v_\phi$ va $v_L = v_\phi - v_r$ sifatida belgilaydi. Biroq o‘zgartirilgan RP1 modelida yuqori hamda pastki chastotalar mos ravishda $v_U = v_\theta$ va $v_L = v_\phi - v_r$ bilan belgilanadi, o‘zgartirilgan RP2 modelida esa chastotalar $v_U = v_\phi$ va $v_L = v_\theta - v_r$ sifatida belgilanadi. RP modelining ortib borayotgan o‘sish va pasayish grafik xatti-harakatlari 9-rasmda tasvirlangan.

XULOSA

Falsafa doktori (PhD) dissertatsiyasi uchun “Muqobil gravitatsiya nazariyalarida qora o‘ralar atrofida optik-energetik jarayonlar” mavzusida olib borilgan tadqiqotlar asosida quyidagi xulosalar keltirildi:

1. Torli bulutning mavjudligi qora o‘raning hodisalar (kosmologik) gorizontining bir oz ortishiga (kamayishiga) olib kelishi va kvintessensial maydon hodisalar gorizontining bir oz ortishiga, kosmologik esa yetarlicha qisqarishiga olib kelishi aniqlandi. Shuningdek, ikkala parametrning ortishi zarrachalarning radial harakatining samarali potensialini pasayishiga olib kelishi ko‘rsatilgan.
2. Aylana orbitalarda zarrachalarning burchak impulsi torli buluti parametri qiymatlari uchun ortib borishi, kvintessensial maydon mavjud bo‘lganda esa impulsning kamayishi ko‘rsatilgan. Bundan tashqari, bu zarrachalarning energiyasi ikkala parametrning oshishi bilan kamayadi.
3. Energiya samaradorligi torli bulut parametri bilan ortib borishi va kvintessensial maydon bo‘lmaganda 70 %gacha yetishi aniqlandi. Biroq u kvintessensial va torli bulut parametrlarining oshishi bilan kamayadi.
4. Kuzatilgan QPO ma’lumotlaridan foydalangan holda GRS 1915+105, GRO J1655-40 va Sgr A* mikrokvazarlarida qora o‘ra massasining cheklovchi qiymatlari birinchi marta kuzatilgan QPO ma’lumotlaridan foydalangan holda torli bulutlar parametri mavjud bo‘lganda olingan. GRO J1655-40 taxminan $8.4 - 18.4\ M_{\odot}$, GRS 1905+105 ning massasi $23.6 - 23.9\ M_{\odot}$ va Sgr A* ning massasi $3.8 - 4.02\ M_{\odot}$.
5. Nol nuqta uzunlik parametri ortganda burilish burchagi sekin tezlik bilan kamayib borishi va bir xil plazma holatida bu qiymat bir xil bo‘lmagan plazmanikiga qaraganda ancha yuqori nuqtaga ega bo‘lishi aniqlandi.
6. Eyler-Gayzenberg parametrining ortishi bilan radial va tangensial chastotalar kamayib, zaryadning ortishi bilan ortishi ko‘rsatilgan. Bundan tashqari, Relyativistik Presessiya modeli uchun yuqori va pastki chastotalar Eyler-Gayzenberg parametrini oshirish uchun ortadi hamda zaryad parametrini oshirish uchun pasayadi.

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

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INSTITUTE OF FUNDAMENTAL AND APPLIED RESEARCH

ABDULVOKHIDOV ALISHER LATIFOVICH

OPTICAL AND ENERGETIC PROCESSES AROUND BLACK HOLE IN ALTERNATIVE THEORIES OF GRAVITY

01.03.01 – Astronomy
01.03.02 – Physics of Cosmos and Astrophysics

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

Tashkent – 2024

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Leading organization:	**Samarkand State University named after Sharof Rashidov**

The defense of the dissertation will be held on "___" _____ 2024 at ___ in the meeting of the Scientific Council No. DSc.03/31.03.2022 T/FM.10.4 at the Institute of Fundamental and Applied Research under the National Research University "TIIAME" (Address: 100000, Tashkent city, Qori Niyazov Street 39, Institute of Fundamental and Applied Research, Hall 108; tel.: 71 237-09-61.; e-mail: info@ifar.uz

The doctoral (PhD) dissertation can be looked through at the Information Resource Center of the Institute of Fundamental and Applied Research under the National Research University "TIIAME" (registered under № ____). (Address: 100000, Tashkent city, 39 Qori Niyazov str., Institute of Fundamental and Applied Research, hall 108; ph.: 71 237-09-61

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Degrees, D. Ph.-M.S.

INTRODUCTION (Annotation of PhD dissertation)

Topicality and demand of the theme of the dissertation. The advancement and refinement of mathematical models concerning various astrophysical occurrences around black holes stand out as one of the foremost priorities in contemporary relativistic astrophysics. Over the past decade, groundbreaking discoveries in observational astronomy have significantly accelerated the pace of progress in developing theoretical and mathematical frameworks for understanding astrophysical phenomena in the vicinity of compact gravitational entities. Concurrently, the quest for a unified theory in fundamental physics necessitates the exploration of new alternative energy theories or modified gravitational frameworks beyond the existing general relativity paradigm. The comparison of these theories with observational and experimental data, along with the determination of critical parameter values for these novel theories, is accomplished through the mathematical simulation of optical-energetic processes occurring near astrophysical black holes.

Alternative and modified theories of gravity are needed to address several shortcomings and discrepancies within the existing framework of general relativity. These theories aim to reconcile the inconsistencies between general relativity and quantum mechanics, provide explanations for phenomena such as dark matter and dark energy, and offer insights into the behavior of gravity under extreme conditions, such as within black holes. Additionally, exploring alternative theories of gravity fosters a deeper understanding of the fundamental nature of space-time and gravity, potentially leading to breakthroughs in our comprehension of the universe. Thus, the study and analysis of curved space in astrophysical research approaches compact objects, and, therefore, the results of astronomical observations are relevant.

In recent years, in our country, more and more attention has been paid to the development of current directions of fundamental and applied research. In particular, the development of astrophysical research, which is one of the promising areas, is an important issue today. The main directions of fundamental research and development and their practical application for the successful development of science in our country are reflected in the Strategy[1]for the further development of the Republic of Uzbekistan from 2022-2026. Therefore, the research of scalarized solutions in higher curvature gravity theories remains one of the urgent issues in the field of fundamental research.

This dissertation work corresponds to the tasks by the following state regulatory documents: Decree of the President of the Republic of Uzbekistan No. PD-4947 "On the Strategy of Actions for the Further Development of the Republic of Uzbekistan" dated February 07, 2017, Resolution of the President of the Republic of Uzbekistan No. PR-2789 "On measures for further improvement of the activities of the Academy of Sciences, organization, management and financing of research activities" dated February 18, 2017 and others.

Conformity of the research to the main priorities of science and technology development of the Republic. The dissertation research has been carried out in

[1] Decree No. PF-60 of the President of the Republic of Uzbekistan dated January 1, 2022 “On the Development Strategy of New Uzbekistan for 2022-2026”

accordance with the priority areas of science and technology in the Republic of Uzbekistan: II. “Power, energy and resource-saving”.

The degree of knowledge of the problem. The study of a theoretical model of the particle motion around black holes have been considered by many scientists, including British (R. Wald, J. Petterson), Russian (A. Zakharov, V. Frolov, I. Novikov), German (C. Laemmerzahl, J. Kunz, A. Grezenbach), Argentinian (L. Amarilla, E. Eiroa), Czech (M. Kolos, J. Vrba), Indian (N. Dadhich, S. Ghosh, P. Joshi, M. Patil), etc. However, the magnetized particle motion around black hole in the presence of string cloud and quintessential field has not been studied. Also, there is no study of circular orbits of magnetized particles at accretion disks.

The theoretical study of the particle motion was developed within the general theory of relativity by Uzbek scientists B.J. Ahmedov, A.A. Abdujabbarov, A.A. Tursunov, and others, and Western scientists R. Wald, S.R., F. de Felice, F. Sorge, and others. However, the question of improving the astrophysical studies for the case when the central object is surrounded by strings’ cloud remains open.

The influence of dark matter on the astrophysical processes around a regular black hole also remains unexplored. The development of theoretical models describing the dynamics of particles around such objects contribute to obtaining limit values for the parameters of modified and/or alternative theories of gravity.

Connection of the topic of the dissertation topic to the scientific works of higher education and research institutions, where the dissertation is carried out. The dissertation was done in the framework of the scientific projects funded by the Ministry of Innovative Development. F-FA-2021-510 "Investigations of nuclear matter of neutron stars in modified gravity".

The aim of the research is the development and improvement of astrophysical models for describing the dynamics of particles and quasi periodic oscillations in the vicinity of black holes in different gravity models.

The tasks of the research:

to explore the motion of test particles around a Schwarzschild black hole in the presence of cloud of strings and the quintessential field;

to study the effect of cloud of strings and the quintessential parameters on the event horizon radius;

to analyze the effective potential for different values of cloud of strings and the quintessential parameters;

to study of the particle energy and angular momentum corresponding to circular orbits in the presence of cloud of strings and the quintessential field;

to analyze the radius of innermost stable circular orbits as a function of cloud of strings and quintessential parameters;

to study the oscillating trajectories in stable circular orbits;

to study the Keplerian frequency and apply it to analysis of twin peak QPOs in the Relativistic Precession model;

to get the constraint values of the mass of the black hole in the microquasars;

to study the deflection angle around black hole with the respect to zero-point length parameter from T-duality;

to analyze the deflection angles for Einstein-Euler-Heisenberg black holes in both non-plasma and plasma mediums;

The object of the research are astrophysical black holes, test particles with zero and nonzero rest mass, quintessence dark matter.

The subject of the research are astrophysical models for studying test particle dynamics near compact gravitational objects, numerical and analytical methods for solving differential equations.

The methods of the research are methods of computational mathematics, methods of theoretical astrophysics, modern methods of mathematical physics, analytical and numerical methods of calculating differential equations for field and particle motion.

The scientific novelty of the research is the following:

It has been obtained that the presence of the cloud of strings causes to slight increase (decrease) in the event (cosmological) horizon and the quintessential field causes increasing in the event horizon slightly, while, the cosmological one decreases sufficiently.

The corresponding values of the parameters of the two fields to the presence/absence of the event horizon, together with the effects of the fields' effects on the event horizon radius have been analyzed. The event horizon is obtained to increase in the presence of strings' clouds, while it decreases with the increase of the quintessential parameter.

The analysis of the effective potential for different values of strings' clouds and quintessential parameters have shown that an increase of both parameters causes a decrease in the effective potential.

Studies of the particle energy and angular momentum corresponding to circular orbits have shown that the angular momentum increases for values of cloud of strings parameter, while in the presence of a quintessential field the momentum decreases.

The analyses of the radius of innermost stable circular orbits (ISCO) as a function of cloud of strings parameter for different values of quintessential parameter have shown show that the energy (angular momentum) of particles decreases (increases) as ISCO radius increases.

It has been shown that the energy efficiency increases with the increase of strings' cloud parameter and reaches up to 70% in the absence of a quintessential field.

It has been shown that in the presence of strings clouds and quintessential parameters, the oscillating trajectories are observed, and the combined effect of both parameters results in stable circular orbits, the trajectories become stable and bounded.

It has been found that the Keplerian frequency goes to a distance in the presence of the quintessential field, and the distance decreases with the increase of quintessential parameter.

The practical results of the research are the following:

For the first time the constraint values of the mass of the black hole in the microquasars GRS 1915+105, GRO J1655-40 and Sgr A* in the presence of the string clouds parameter using observed QPO data have been obtained as follows: mass of the GRO J1655-40 is about $8.4 - 18.4\ M_{\odot}$, mass of GRS 1905+105 is $23.6 - 23.9\ M_{\odot}$

and the mass of Sgr A* is $3.8 - 4.02\ M_{\odot}$.

The analysis of deflection angle of photons around black hole with the respect to zero-point length parameter from T-duality have shown that the angle decreases at very slow rate when zero-point length parameter increases.

It has been obtained that the deflection angle decreases with slow rate when zero-point length parameter increases and in the case of uniform plasma this value gets a considerably high point rather than that of non-uniform plasma.

It has been shown that the radial and tangential frequencies decrease for increasing of Euler-Heisenberg parameter and increase for increasing of charge. It has been also obtained that upper and lower frequencies for Relativistic Precession model increase for increasing Euler-Heisenberg parameter and decrease for increasing charge parameter.

The reliability of the research results provided by applying modern proven methods of mathematical physics, computational mathematics, and relativistic astrophysics. The results were obtained strictly within the mathematical apparatus of general relativity and theoretical physics. Modern numerical and analytical methods of calculation are also used, and the results are compared with available observational data and the results of other authors. The structured conclusions of the thesis correspond to the basic rules of astrophysics of compact objects.

The scientific and practical significance of the research results. The scientific significance of the research results is found that the analysis of solutions for black holes in different gravity models can be a useful tool for studying various theoretical models of gravity.

The practical significance of the research results is that they can play a role in the construction of dynamic and stationary space-time constraints of the black hole with the observations twin peak QPOs.

Application of the research results. Based on the developed mathematical models of the particle dynamics of charged and magnetized particles in the modified theory of gravity the followings have been developed:

scientific results obtained on the motion of magnetized particles and magnetic effects have been used by scientists from Fudan University (FU) in Shanghai (FU, China, May 16, 2024 reference);

the magnetic value of the particles and the influence of the deformed space on the orbits of such particles were calculated. Results on the photon orbits have been used in the works of foreign researchers, in foreign journals with a high impact factor (Physical Review D, 2024; submitted; European Physical Journal C, 2024, submitted) are used in 3 published scientific papers to describe the effects of magnetized particles around a rotating black hole;

as a result, it is possible to obtain information about the magnetized particles dynamics around compact objects within the framework of modified gravity theories.

Testing of the research results. The research results were reported and discussed at 1 international conference and 3 local scientific conferences.

Publication of research results. 6 research papers were published on research results, 3 of them – in the international scientific journals recommended by Supreme

Attestation Commission at the Ministry of higer education, science and innovations of the Republic of Uzbekistan.

Volume and structure of the dissertation. The dissertation consists of an introduction, four chapters, a conclusion and references, all in 82 pages.

THE MAIN CONTENT OF THE DISSERTATION

The introduction of the dissertation indicates the relevance and necessity of the topic, the correspondence of the research to the priority directions of development of science and technology of the republic, the degree of knowledge of the problem, its connection with the research plans of the higher educational institution in which the dissertation was carried out, and the purpose, objectives, object of research, brief information about the subject, methods, scientific novelty, practical result, reliability, scientific and practical significance of the results, introduction of the results into practice, approval of the results, publication of the results, as well as the structure and scope of the dissertation.

The first chapter, entitled 'Review Literature' provides an overview of research in the field of particle dynamics and different solutions of black holes in different gravity models, including Kiselev black hole solutions, lack holes in T-duality and Einstein-Euler-Hesisenberg model. A review of studies on quasiperiodic oscillation (QPO) models within the framework of general relativity or alternative theories of gravity has been also discussed within this chapter.

The second chapter entitled as 'Test particles and quasiperiodic oscillations around Kiselev black hole with cloud of strings' is devoted to study the dynamics of test particles around a Schwarzschild black hole surrounded by quintessence and immersed in a scalar string cloud field. We start our study by defining the possible values of quintessence and cloud of string parameters corresponding to the existence of the black hole horizon for the fixed values of the parameter of the equation of state for dark energy. We also study the behavior of the effective potential for the circular motion of test particles, energy, and angular momentum of the particles together with innermost stable circular orbits (ISCOs).

We investigate the fundamental frequencies in the particles' oscillations along stable circular orbits. We related the stability of the orbits to the Lyapunov exponent, and the chaotic behavior is studied graphically. Finally, we apply the fundamental frequencies to describe quasiperiodic oscillations (QPOs), and it is obtained that in the presence of both fields low-frequency twin-peak QPOs are not observed. Also, we obtain constraint values for the string clouds parameter and mass of the black hole candidates located in the center of the microquasars GRO J1655-40 & GRS 1915+105 and Milky Way galaxy. Overal, it has been performed the analysis of the dynamics of the test particles around quintessential BH surrounded by a cloud of strings with the aim of applying it to study QPOs.

The static and spherically symmetric black hole solution, associated with quintessence and cloud of strings is described by the following line element within the spherical coordinates $x^{\mu} = (t, r, \theta, \varphi)$

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

with the lapse function

$$f(r) = 1 - \alpha - \frac{2M}{r} - \frac{\gamma}{r^{3\omega_q+1}} \tag{2}$$

where M is the black hole's.

For the perfect fluid distribution of matter/energy, the EoS parameter takes the value in the range of $-1 < \omega_q < -\frac{1}{3}$, and when $\omega_q = -1$ it recovers the cosmological constant. Therefore, as test values, throughout this paper, we work with the cases $\omega_q = -\frac{1}{2}$ and $\omega_q = -\frac{2}{3}$:

$$f(r) = 1 - \alpha - \frac{2M}{r} - \begin{cases} \gamma r^{\frac{1}{2}}, & \omega_q = -\frac{1}{2} \\ \gamma r, & \omega_q = -\frac{2}{3} \end{cases} \tag{3}$$

In general, the radius of the event horizon of a spherically symmetric black hole can be defined by $g^{rr} = 0$.

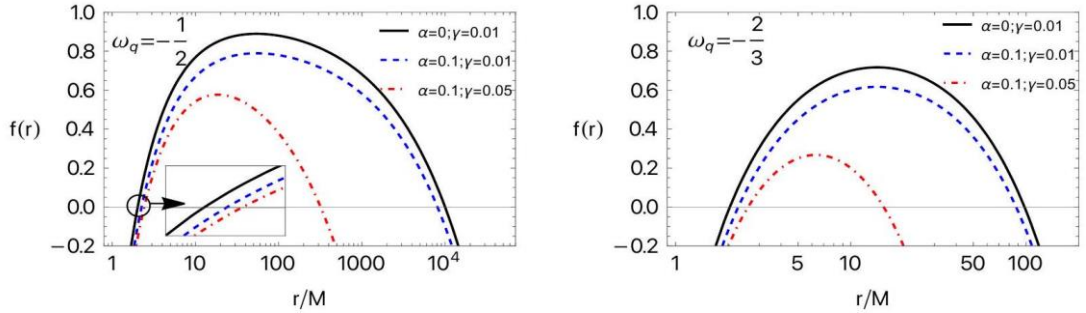

Figure 1. Dependence of event horizon radius on the string clouds α for different values of γ and ω_q.

Figure 1 show radial dependence of the metric function $f(r)$ for the different values of α, and γ in the cases: $\omega_q = -\frac{1}{2}$ and $-\frac{2}{3}$. One can see from both panels that the lines cross zero (the metric function takes zero) values at two different distances, representing the event and cosmological-like horizons (due to quintessential field). In the presence of both strings' clouds and the quintessential field, the horizons come close to each other. Moreover, it is also seen that the radius of a cosmological-like horizon is very sensitive.

We have explored stable circular orbits. The following conditions determine such orbits of a test particle around a spherically symmetric black hole:

$$V_{\text{eff}} = \mathcal{E},\ V'_{\text{eff}} = 0. \tag{4}$$

The expressions for the angular momentum and energy of test particles corresponding to circular orbits take the form

$$\mathcal{L}^2 = -\frac{r^2\left(\gamma + 2Mr^{3\omega_q} + 3\gamma\omega_q\right)}{2(3M + (\alpha-1)r)r^{3\omega_q} + 3\gamma\left(\omega_q + 1\right)} \tag{5}$$

$$\mathcal{E}^2 = -\frac{2r^{-3\omega_q-1}(\gamma + (2M + (\alpha-1)r)r^{3\omega_q})^2}{2(3M + (\alpha-1)r)r^{3\omega_q} + 3\gamma\left(\omega_q + 1\right)} \tag{6}$$

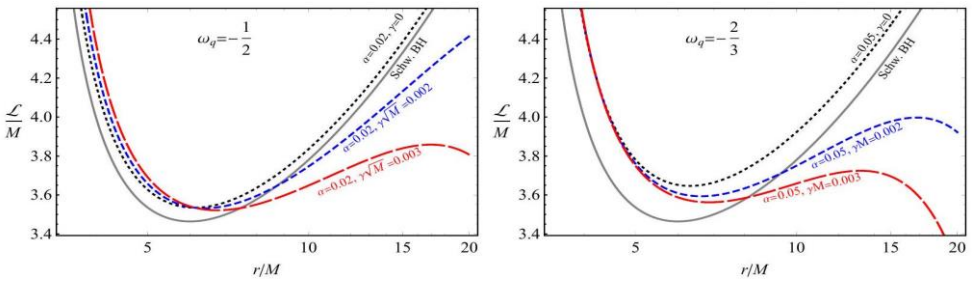

Figure 2. The angular momentum of test particles in circular orbits as a function of radial coordinates for different values of the parameters α, γ, and ω_q.

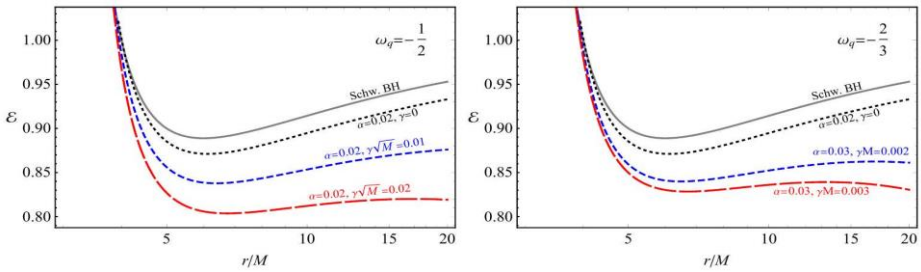

Figure 3. The energy of test particles at circular orbits around the black hole as a function of the radial coordinate for the different values of α, γ, and ω_q.

Figure 2 demonstrates the radial dependence of the angular momentum of test particles corresponding to circular orbits around Schwarzschild black holes in string clouds and the quintessential field for the different values of spacetime parameters. It is observed from the figure that in the presence of the string clouds, the value of the angular momentum increases, while the presence of the quintessential field causes it to decrease. One can note that the effect of γ is dominant at larger distances, affecting dark matter.

At larger distances, there is a maximum in the angular momentum and the maximum decreases and shifts towards the central BH due to the increase of both quintessential field parameters. Figure 3 shows the radial dependence of the energy of the test particles corresponding to circular orbits around quintessence BH in string clouds for different values of the parameters α, γ, and ω_q. The innermost stable circular orbit (ISCO) should satisfy the condition $\partial_{rr} V_{\text{eff}}(r_{\text{ISCO}}) = 0$ and/or $\partial_r \mathcal{L} = 0$ together with conditions (4). The corresponding equation for ISCO radius takes the following form:

$$\gamma 6M\left[\omega_q\left(3\omega_q - 4\right) - 2\right] + (\alpha - 1) r_{\text{ISCO}}\left(9\omega_q^2 - 1\right)\Big\} - \frac{2M}{r_{\text{ISCO}}^{-3\omega_q}}\left[6M + (\alpha - 1) r_{\text{ISCO}}\right] - \frac{3\gamma^2}{r_{\text{ISCO}}^{3\omega_q}}\left(\omega_q + 1\right)\left(3\omega_q + 1\right) = 0. \qquad (7)$$

One can easily see from Eq. (7) that in the Schwarzschild case when $\alpha = \gamma = 0$ the ISCO radius $r_{ISCO} = 6M$. However, Eq. (7) is quite complicated to be solved analytically. Therefore, we present graphical analyses of the behavior of ISCO radius with respect to the variation of the quintessential and string cloud parameters. ISCO radius as a function of α parameter is shown in Fig. 4 for the different values of quintessence parameters. It is seen that ISCO enlarges in the presence of both string clouds and the quintessential field.

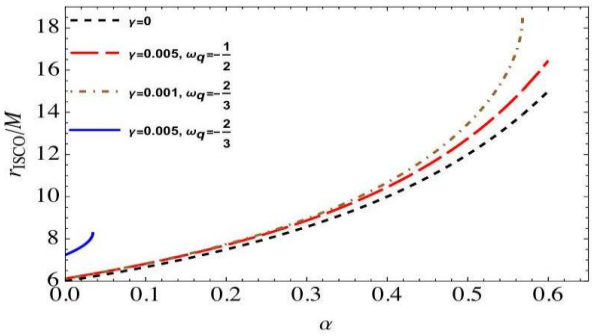

Figure 4. ISCO radius as a function of the parameter α for different cases of γ and ω_q.

The dynamics of the charged test particles around BHs explain the existence of QPOs based on quasi-harmonic oscillations of the particles in the radial and angular directions. We consider the upper and lower frequencies of twin-peaked QPOs in the relativistic procession (RP) model. RP model defines the upper and lower frequencies by the frequencies of the radial, vertical, and orbital oscillations as $\nu_U = \nu_\phi \& \nu_L = \nu_\phi - \nu_r$.

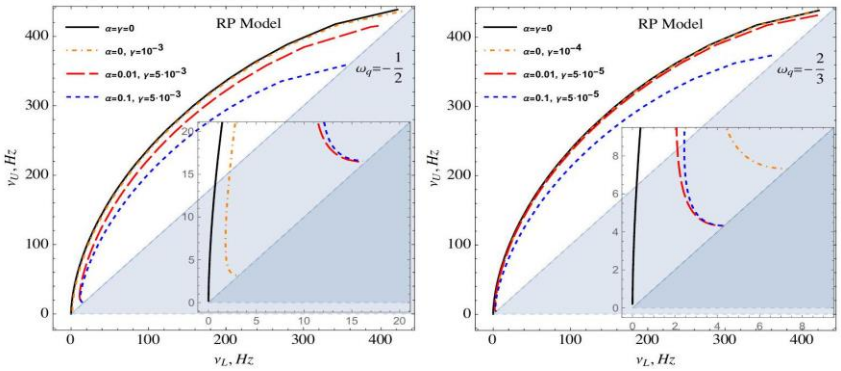

Figure 5. Relationships between upper and lower frequencies around Kiselev black hole with string clouds for different α, γ, and ω_q. Here, we have chosen $M = 10M_\odot$.

In Fig. 5 we have shown the diagram for upper and lower frequencies of twin peak QPOs around a black hole in the presence of the quintessential field and string clouds in the relativistic precession model. The curves in the diagram for $\nu_U - \nu_L$ are compared with the Schwarzschild case in both $\omega_q = -1/2$ and $-2/3$ cases and obtained that when $\omega_q = -1/2$, the presence of a quintessential field with $\gamma = 10^{-3}$ cause to slightly decrease the frequencies at high-frequency QPOs. It is also observed that low-frequency QPOs below about 5 Hz are not observed, while in the presence of a cloud of strings with $\alpha = 0.01$, it shifts up to about 20 Hz. However, at, $\omega_= -\frac{2}{3}$ the effect of γ on the minimum upper and lower frequencies can be observed more strongly than α. It is also seen that with the increase of α the upper and lower frequencies of high-frequency QPOs sufficiently decrease for both values of ω_q.

The third chapter entitled 'Weak gravitational lensing of black hole from Tduality in plasma' is devoted to investigate the impact of a plasma environment on gravitational weak lensing around a black hole from the perspective of T duality. Our results demonstrated that the deflection angle of light rays around the black hole is notably affected by the parameter l_0, with an increase leading to a decrease in the deflection

angle, while the effect of plasma on the deflection angle is the opposite. We also consider different types of plasma distributions, including uniform $\omega_e =$ const, Singular Isothermal Sphere medium, and NonSingular Isothermal gas sphere plasma. We have analyzed the total magnification of the image source due to gravitational weak lensing, taking into account the effect of parameter l_0 related to T-duality in the presence of plasma around the black hole.

Here we plan to apply the weak lensing formalism for the gravitational lensing around spherically symmetric BH solution

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2), \tag{8}$$

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$$f(r) = 1 - \frac{2Mr^2}{\sqrt{(l_0^2+r^2)^3}} \tag{9}$$

where l_0 is the zero-point length of spacetime from T-duality, M is the black hole's mass. We consider the weak field regime.

For a wide range of values of l_0 and ω_0/ω, in Fig. 6 the deflection angle of light rays around BH is represented as a function of the impact parameter b. The dependence of the deflection angle on plasma frequency ω_0/ω and T-duality parameter l_0 for fixed values of impact parameter is represented in other two plots on the bottom of Fig. 6. These graphs suggest that the existence of the plasma medium properties causes a bending of the deflection angle of light rays around BH. Further, the angle at which light rays are bent almost does not change at all when the parameter l_0 is increased for the fixed frequency. By contrast, with the rise of plasma frequency the value of the deflection angle demonstrates a gradual increase with the same manner in different values of parameter l_0 from T-duality. With increasing impact parameter b, the gravitational deflection angle approaches zero.

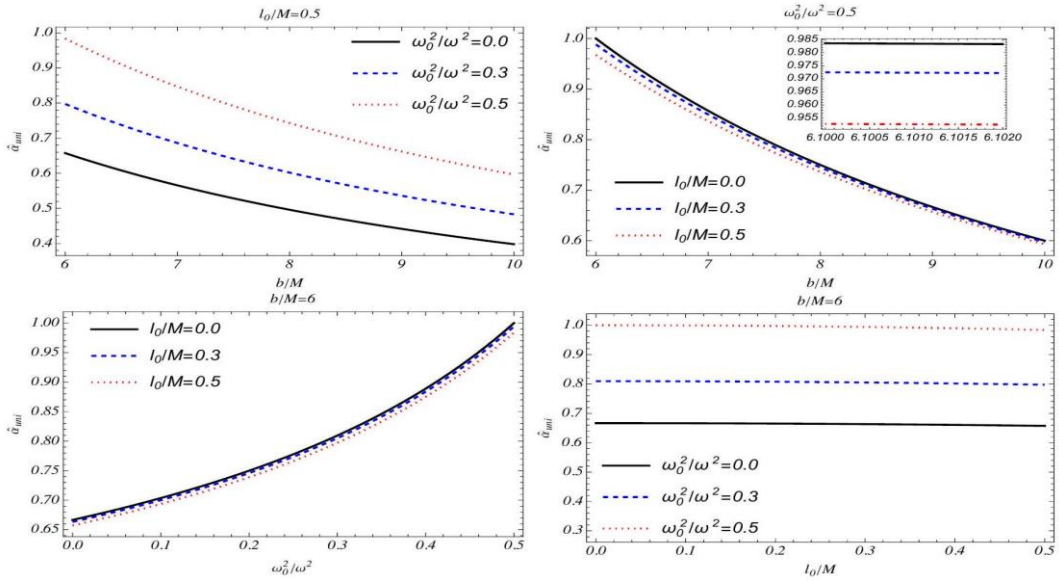

Figure 6. The dependence of the deflection angle $\hat{\alpha}_{uni}$ on the impact parameter b, parameter l_0 for different values of parameter l_0/M and plasma medium ω_e^2/ω^2. The corresponding fixed parameter used is $b = 6$.

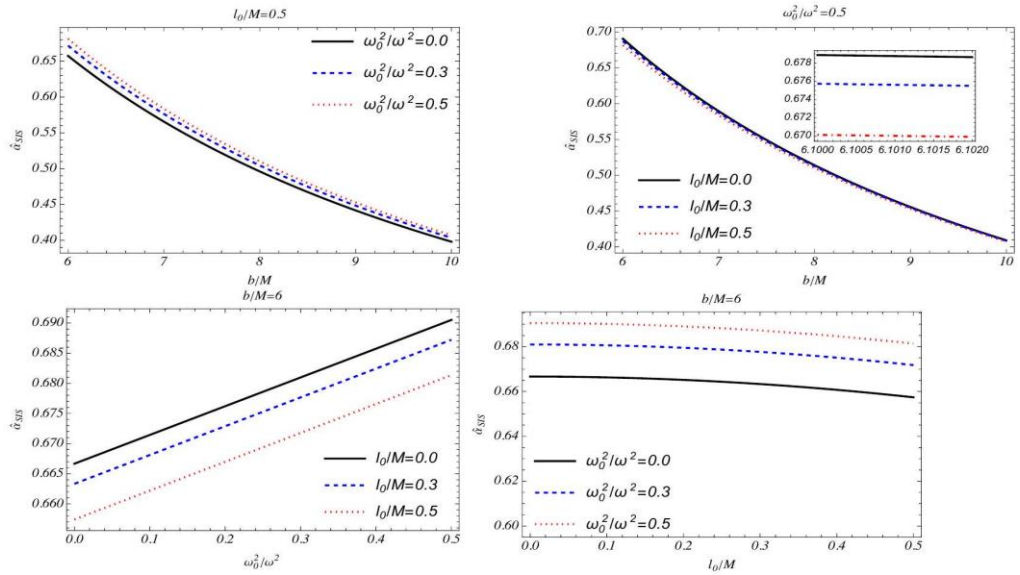

Figure 7. The effect of the impact parameter b, parameter l_0 on the deflection angle $\hat{\alpha}_{SIS}$ for different values of parameter l_0/M and plasma medium ω_c^2/ω^2. The associated fixed parameter is $b/M = 6$.

The top panels of Fig. 7 correspond to the two different plots illustrating the dependence of the deflection angle on the impact parameter b for fixed values of the parameter l_0 and ratio of plasma frequency and photon frequency ω_c/ω. From these plots, one may easily see that the gravitational deflection angle tends to zero with the rise of the impact parameter b. The bottom panels of Fig. 7 show that the value of the deflection angle relies on the change of plasma frequency ω_c/ω in non-uniform plasma case and parameter l_0 from T-duality. The bottom right figure illustrates that the deflection angle of the light rays slightly decreases in the influence of parameter l_0 and that the opposite is true from the left graph under the impact of a non-uniform plasma medium.

The fourth chapter entitled 'Weak gravitational lensing and fundamental frequencies of Einstein-Euler-Heisenberg black hole' is devoted to analyze the gravitational weak lensing and fundamental frequencies in the framework of the EinsteinEuler-Heisenberg (EEH) black hole. We compute the deflection angle of light by the EEH black hole in weak field limits. Which represents that the bending of light is a global and topological effect. For this purpose, we deduce the Gaussian curvature and apply the Gauss-Bonnet theorem (GBT). Furthermore, we determine the deflection angle at which light is deflected by a plasma medium. We also look into how an EEH black hole behaves graphically in vacuum and plasma medium. Moreover, we study the fundamental frequencies with three different models of EEH black hole.

The metric for EEH BH in a static and spherically electrically charged form as,

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (10)$$

The metric case $f(r)$ for electric field is defined as

$$f(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - \frac{\mu Q^4}{20r^6} \quad (11)$$

where M, Q and μ represents the mass of the BH, electric charge and EulerHeisenberg parameter respectively.

Fig. 8, shows the behavior of deflection angle α versus impact parameter b for varying the values of μ and Q in left and right panel, respectively. In the left plot we take $M = 1, Q = 0.7$ and for different values of parameter $: \mu = 0,50,100,150$. We analyze that the deflection angle for the higher values of μ increases and decreases for the smaller values of μ, for the domain of impact parameter $4 \leq b \leq 15$. In the right plot we consider $Q = 0,0.3,0.6,0.9$, for the fixed $M = 1$ and $\mu = 50$ in the EEH BH. Deflection angle behaviour that gradually decreases for larger values of Q. We take the domain of black hole for plots is $4 \leq b \leq 15$.

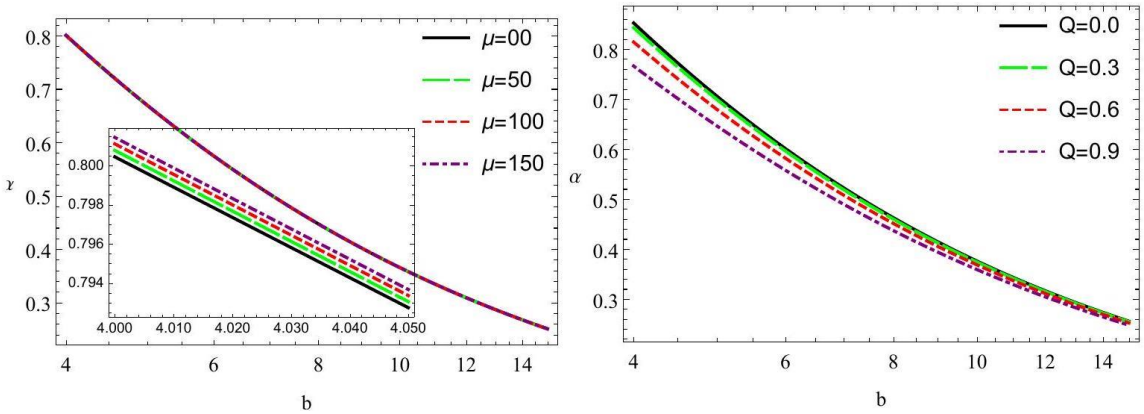

Figure 8. Deflection angel α versus impact parameter b for varying values of μ (Left graph) and Q (Right graph) for vacuum case.

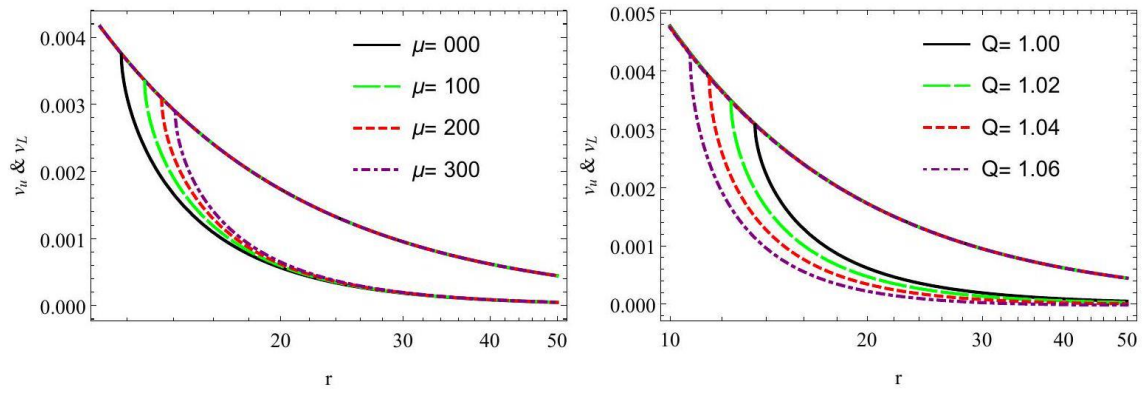

Figure 9. RP model: frequencies v_u&v_L along radial coordinate r for fixed values $M = 1, Q = 1, \mu = 200$, where variable values are shown in plot legend.

The standard relativistic precession (RP) model defines the upper and lower frequencies as $v_U = v_\phi$ and $v_L = v_\phi - v_r$, respectively. However, in the modified RP1 model, the upper and lower frequencies are denoted by $v_U = v_\theta$ and $v_L = v_\phi - v_r$, respectively, whereas in the modified RP2 model, the frequencies are specified as $v_U = v_\phi$ and $v_L = v_\theta - v_r$. The ascending and descending graphical behaviors of the RP model with increasing are illustrated in Fig. 9.

CONCLUSIONS

The following conclusions were presented on the basis of research carried out on the topic of "Optical and energetic processes around black hole in alternative theories of gravity" for the Doctor of Philosophy (PhD) dissertation:

1. It has been obtained that the presence of the cloud of strings causes to slight increase (decrease) in the event (cosmological) horizon of black hole and the quintessential field causes increasing in the event horizon slightly, while, the cosmological one decreases sufficiently. It has been also shown that an increase of both parameters causes a decrease in the effective potential of radial motion of particles.
2. It has been shown that the angular momentum of particles at circular orbits increases for values of string cloud parameter, while in the presence of a quintessential field, the momentum decreases. Moreover, the energy of these particles decreases with the increase of both parameters.
3. It has been obtained that the energy efficiency increases with string cloud parameter and reaches up to 70 % in the absence of a quintessential field. However, it decreases with increasing quintessential and string cloud parameters.
4. For the first time the constraint values of the mass of the black hole in the microquasars GRS 1915+105, GRO J1655-40 and Sgr A* in the presence of the string clouds parameter using observed QPO data have been obtained as follows: mass of the GRO J1655-40 is about $8.4 - 18.4\ M_{\odot}$, mass of GRS 1905+105 is $23.6 - 23.9\ M_{\odot}$ and the mass of Sgr A* is $3.8 - 4.02\ M_{\odot}$.
5. It has been obtained that the deflection angle decreases with slow rate when zero-point length parameter increases and in the case of uniform plasma this value gets a considerably high point rather than that of non-uniform plasma.
6. It has been shown that the radial and tangential frequencies decrease for increasing of Euler-Heisenberg parameter and increase for increasing of charge. It has been also obtained that upper and lower frequencies for Relativistic Precession model increase for increasing Euler-Heisenberg parameter and decrease for increasing charge parameter.

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".

АНДИЖАНСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ ИМЕНИ З.М. БАБУРА
ИНСТИТУТ ФУНДАМЕНТАЛЬНЫХ И ПРИКЛАДНЫХ ИССЛЕДОВАНИЙ

АБДУЛВОХИДОВ АЛИШЕР ЛАТИФОВИЧ

ОПТИКО-ЭНЕРГЕТИЧЕСКИЕ ПРОЦЕССЫ В ОКРЕСТНОСТИ ЧЕРНЫХ ДЫР В АЛЬТЕРНАТИВНЫХ ТЕОРИЯХ ГРАВИТАЦИИ

01.03.01-Астрономия
01.03.02 – Физика космоса и астрофизика

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

Ташкент – 2024

Тема диссертации доктора философии (PhD) по физикоьматематическим наукам зарегистрирована в Высшей аттестационной комиссии при Кабинете Министров Республики Узбекистан за номером № B2024.1.PhD/FM1025.

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

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Защита диссертации состоится «__» _____ 2024 года в ___ часов на заседании Научного совета DSc.03/31.03.2022.T/FM.10.04 при Института фундаментальных и прикладных исследований национального исследовательского университета "ТИИИМСХ". Адрес: 100000, г.Ташкент, улица Кори Ниязова 39, Тел.: +998 71 237-09-61; e-mail: info@ifar.uz

Диссертация зарегистрирована в Информационно-ресурсном центре Института фундаментальных и прикладных исследований Национального исследовательского университета "ТИИИМСХ". (регистрационный номер ___). С диссертацией можно ознакомиться в Библиотеке Института фундаментальных и прикладных исследований Национального исследовательского университета "ТИИИМСХ". Адрес: 100000, г.Ташкент, улица Кори Ниязова 39, Тел.: +998 71 237-09-61

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ВВЕДЕНИЕ (аннотация диссертации доктора философии (PhD))

Целью исследования является разработка и совершенствование астрофизических моделей для описания динамики частиц и квазипериодических колебаний в окрестностях черных дыр в различных моделях гравитации.

Объектом исследования являются астрофизические черные дыры, пробные частицы с нулевой и ненулевой массой покоя, квинтэссенция темной материи.

Научная новизна исследования заключается в следующем:

Установлено, что наличие облака струн приводит к незначительному увеличению (уменьшению) горизонта событий (космологического), а поле квинтэссенции вызывает незначительное увеличение горизонта событий, тогда как космологическое существенно уменьшается.

Показано, что горизонт событий увеличивается при наличии струнных облаков и уменьшается с увеличением квинтэссенционного параметра.

Анализ эффективного потенциала для различных значений струнных облаков и параметров квинтэссенции показал, что увеличение обоих параметров приводит к уменьшению эффективного потенциала.

Исследования энергии и углового момента частиц, соответствующих круговым орбитам, показали, что угловой момент увеличивается при значениях параметра облака струн, тогда как при наличии квинтэссенционного поля импульс уменьшается.

Анализ радиуса внутренних устойчивых круговых орбит (ISCO) в зависимости от параметра облака струн для различных значений квинтэссенционного параметра показал, что энергия (угловой момент) частиц уменьшается (увеличивается) с увеличением радиуса ISCO.

Показано, что энергетическая эффективность возрастает с увеличением параметра облака струн и достигает 70% при отсутствии квинтэссенционного поля.

Показано, что при наличии струнных облаков и квинтэссенционных параметров наблюдаются колеблющиеся траектории, а совместное воздействие обоих параметров приводит к устойчивым круговым орбитам, траектории становятся устойчивыми и ограниченными.

Обнаружено, что кеплерова частота уходит на расстояние при наличии квинтэссенционного поля, причем расстояние уменьшается с увеличением квинтэссенционного параметра.

Применение результатов исследования. На основе разработанных математических моделей динамики заряженных и намагниченных частиц в модифицированной теории гравитации разработаны:

полученные научные результаты по движению намагниченных частиц и магнитным эффектам были использованы учёными Фуданьского университета (ФУ) в Шанхае (ФУ, Китай, справка от 16 мая 2024 г.);

рассчитаны магнитная величина частиц и влияние деформированного

пространства на орбиты таких частиц. Результаты по орбитам фотонов использованы в работах зарубежных исследователей, в зарубежных журналах с высоким импакт-фактором (Physical Review D, 2024; в печати; European Physical Journal C, 2024, в печати), использованы в 3 опубликованных научных статьях для описания эффекты намагниченных частиц вокруг вращающейся черной дыры;

в результате можно получить информацию о динамике намагниченных частиц вокруг компактных объектов в рамках модифицированных теорий гравитации.

Объем и структура диссертации. Диссертация состоит из введения, четырех глав, заключения и списка литературы, всего на 82 страницах.

E’LON QILINGAN ISHLAR RO‘YXATI
СПИСОК ОПУБЛИКОВАННЫХ РАБОТ
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