On the Physical Nature of the Source of Ultraluminous X-ray Pulsations

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ABSTRACT

To reconcile the observed unusual high luminosity of NuSTAR X-ray pulsations from M82X-2 with the most extreme violation of the Eddington limit, and in view that the persistent X-ray radiation from M82X-2 almost precludes the possibility of common pulsars, we tackle the problem by the implications of microscopic theory of black hole (MTBH). The preceding developments of MTBH are proved to be quite fruitful for the physics of ultra-high energy (UHE) cosmic-rays. Namely, replacing a central singularity by the infrastructures inside event horizon, subject to certain rules, MTBH explains the origin of ZeV-neutrinos which are of vital interest for the source of UHE-particles. The M82X-2 is assumed to be a spinning intermediate mass black hole resided in final stage of growth. As a corollary, the thermal blackbody X-ray emission arisen due to the rotational kinetic energy of black hole escapes from event horizon through the vista to outside world that detected as ultraluminous X-ray pulsations. The M82X-2 indeed releases $\sim 99.6\%$ of its pulsed radiative energy predominantly in the X-ray bandpass $0.3 - 30$ keV. We derive a pulse profile and give a quantitative account of energetics and orbital parameters of the semi-detached X-ray binary containing a primary accretor M82X-2 of inferred mass $M \approx 138.5 - 226 M_\odot$ and secondary massive, $M_2 > 48.3 - 64.9 M_\odot$, O/B-type donor star with radius of $R > 22.1 - 25.7 R_\odot$, respectively. We compute the torque added to M82X-2 per unit mass of accreted matter which yields the measured spin-up rate.

Subject headings: black hole physics; accretion: accretion discs; X-rays: binaries; X-rays: individual (NuSTAR J095551+6940.8)

1. Introduction

The physical nature of the accreting off-nuclear point sources in nearby galaxies, so-called the ultraluminous X-ray sources (ULXs), has been an enigma because of their high energy output characterized by super-Eddington luminosities up to two orders of magnitude higher than those observed from Galactic X-ray binaries, and unusual soft X-ray spectra with blackbody emission around $\lesssim 0.3$ keV and a downturn above $\sim 5$ keV (e.g. Fabbiano et al. [1989]; King et al. [2001]; Swartz et al. [2004]; Roberts [2007]; Gladstone et al. [2009]; Feng & Soria [2011]; Liu [2011]; Walton et al. [2011]; Liu et al. [2013]; Motch et al. [2014]). In spite of significant efforts in more than three decade since the discovery of ULXs, the astronomers have not yet clarified their nature. Without care of the historical justice and authenticity, it should be emphasized that the ULX sources have attracted a great deal of observational and theoretical attention, in part because their luminosities suggest that they may harbor intermediate mass black holes (IMBHs) with an ubiquitous feature of the mass fits of more than $10^2 - 10^4 M_\odot$ (Feng & Soria 2011; Colbert & Mushotzky 1999; Makishima et al. 2000). A strong argument in favor of IMBHs is the presence of a soft, 0.10.2 keV component in their spectra [Kaaret et al. [2003]; Miller et al. [2003, 2004]. The hyperluminous X-ray sources with luminosities $\geq 10^{41}$ erg s$^{-1}$ are thought to be amongst the strongest IMBH candidates (Matsumoto et al.)
Assuming the emission is isotropic, in general, the extreme luminosities of ULXs suggest either the presence of IMBHs and sub-Eddington accretion (e.g. Komossa & Schulz 1998; Miller & Colbert 2004; Dewangan et al. 2006; Stobbart et al. 2006; Patruno et al. 2006; Portegies et al. 2007; Kong et al. 2007; Casella et al. 2008; Feng & Kaaret 2010; Liu et al. 2013; Feng & Soria 2011; Walton et al. 2013; Pasham et al. 2014), or stellar-mass black holes ($M \leq 10 M_\odot$) that are either breaking or circumventing their Eddington limit via a narrow beam then binaries can form extreme ULXs with the X-ray luminosity of $L_X \gtrsim 10^{42}$ erg s$^{-1}$. They envisage that these systems are not only limited to binaries with stellar-origin black hole accretors, but also can be identified with neutron star systems. For the latter the typical donors are evolved low-mass ($2 M_\odot$) helium stars with Roche lobe overflow rate of $\sim 10^{-2} M_\odot yr^{-1}$. This study does not prove that any particular extreme ULX is a regular binary system. Or, Fragos et al. (2015) performed a population synthesis studies of ULXs with neutron star accretors. Combining binary population synthesis and detailed mass-transfer models, they conclude that the binary system that formed M82X-2 is most likely less than 50 Myr old and contains a donor star which had an initial mass of approximately $8-10 M_\odot$, while the NS’s progenitor star had an initial mass in the $8-25 M_\odot$ range. Or, Mushtukov et al. (2015) study properties of luminous X-ray pulsars using a simplified model of the accretion column. The resulting luminosity of NS pulsars may can reach values of the order of $10^{40}$ erg s$^{-1}$ for the magnetar-like magnetic field, since the equilibrium, where the Alfvén radius matches the co-rotation radius, indicates a magnetic field of $B \gtrsim 10^{14}$G, and long spin periods ($P \gtrsim 1.5 s$). They conclude that a substantial part of ULXs are accreting neutron stars in binary systems. All these proposals have own advantages and difficulties. Nevertheless, no single theory has been invented yet which successfully addresses the solution to the problems involved. The aforementioned studies are not exception to the rule that as phenomenological approaches they suffer from own difficulties. Namely, they are strongly model dependent, and subject to many uncertainties and controversies. The physics is obscured by multiple arbitrary assumptions and proliferation of a priori free parameters involved, while a consistent complete theory would not have so many free parameters. So, the issue is still controversial, and these exotic results and conclusions are still lame and for sure not proven by the authors. For example, Wiktorowicz et al. (2013) have evoked the possibility that the transferred mass is efficiently accreted onto a compact object and converted to X-ray luminosity in the full range of possible mass accretion rates, which is in contrast with the generally accepted view that the conversion...
efficiency decreases with increasing mass accretion rate (e.g., Pontanen et al. (2007)). Or, in case of model of the accretion column, a necessary condition for the X-ray luminosity to exceed the Eddington limit is a certain degree of asymmetry in the distribution of matter over the Alfvén surface (Basko & Sunyaev 1976), which is a qualitative picture, perhaps, but not quantitative one, or a $B \gtrsim 10^{14}$ G magnetic field of a magnetar-like pulsar is rather above the quantum limit, etc. We will not be concerned here with the actual discussion of these results, which require further extensive and careful analysis, in order one could verify the proposed estimates and constrain model parameters. There were still many open key questions arisen inevitably that we have no understanding of ULX physics. A main physical issue whether ULXs are powered by IMBHs or normal stellar black holes to date is unresolved, primarily because we do not have dynamical mass measurements of the compact objects that power ULXs. So, it is premature to draw conclusions and only time will tell whether any of these intriguing proposals is correct and which of the hypothesized ULX scenario is actually realized in nature.

1.1. The ultraluminous X-ray pulsations

The most striking is the recent revolutionary NuSTAR discovery of the first rare and mighty ultraluminous X-ray pulsations with the maximum luminosity $L(3-30\text{keV}) = 4.9 \times 10^{39} \text{erg s}^{-1}$, of average period 1.37 s with a 2.5-day sinusoidal modulation (Bachetti et al. 2014), coming from an ultraluminous source, NuSTAR J095551+6940.8, located nearby starburst galaxy M82 (NGC 3034). The pulsed emission centroid is spatially consistent with the location of a variable M82X-2 which further secures the association of the pulsating source with M82X-2. Detection of coherent pulsations, a binary orbit, and spin-up behavior indicative of an accretion torque unambiguously, allow to feature the M82X-2 as mass-exchange binary that contains a nondegenerate secondary donor star. Eventually, in addition to the orbital modulation, about an evident linear spin-up of the pulsar was reported by (Bachetti et al. 2014), with $\dot{p} \simeq -2 \times 10^{-10} \text{s}^{-1}$ over the interval from modified Julian days 56696 to 56701 when the pulse detection is most significant. Phase connecting the observations enables detection of a changing secular spin-up rate over a longer timespan as well as erratic variations. Future observations will show whether the current spin-up rate is secular. Kluzniak & Lasota (2015) point out that the spin-up to luminosity ratio $10^{-50}$ (erg s)$^{-1}$ is an order of magnitude lower than the typical ratio observed in the X-ray pulsars, which makes an interpretation of the data in terms of a strongly magnetized X-ray pulsar quite challenging. In absolute terms, this spin-up rate is orders of magnitude higher than the values measured in the usual accretion powered X-ray pulsars (Bildsten et al. 1997; Ziolkowski 1985).

1.2. Key objections

A current understanding of NuSTAR discovery is quite complicated. At first glance it seems as though the NuSTAR team has demonstrated that the super-Eddington accretion is also possible in ULXs hosting a neutron star, because it is generally believed that the pulsating X-ray sources are magnetic neutron stars which are accreting matter from a binary companion (Pringle & Rees 1972; Davidson & Ostriker 1973; Lamb et al. 1973; Lamb 1975). Therefore, it seems that there is nothing left but M82X-2, which until recently astronomers had thought was a black hole, is the brightest magnetic neutron star system ever recorded. This point of view is widely quoted in literature and, at first sight, seems eminently reasonable. However, deeper examination raises several disturbing questions, if the above result is really valid. Even though, if for a moment we take the classical accreting neutron star pulsar system as a basic assumption, note that this model is not flawless. The actual mechanism by which pulsars convert the rotational energy of the neutron star into the observed pulses is poorly understood. Many theoretical models have been proposed that account for such features, but no single one is compelling (Sieber & Wielebinski 1981; Michel 1982).

Explaining periodic source M82X-2 that obviously has black hole energetics with a $\sim 1.4 M_\odot$ compact object using the accreting neutron star pulsar systems is extremely challenging, because of several problems we encountered. The difficulty becomes apparent when one follows the three objections, which together constitute a whole against the claim that M82X-2, perhaps, is a common
pulsar: 1) The NuSTAR team discovery is the most extreme violation of the so-called Eddington limit, i.e. the pulsed luminosity of M82X-2 reaches about $\sim 26.9$ times brighter than the theoretical threshold at the spherical accretion for $\sim 1.4 M_\odot$ stellar-mass black holes where the outward pressure from radiation balances the inward pull of gravity of the pulsar. The accretion is inhibited once radiation force is equal or greater than gravity force. 2) The difficulty is brought into sharper focus by considering the association with M82X-2, which is featured with high luminosity ($\sim 1.8 \times 10^{40} \text{erg s}^{-1}$) of additional persistent continuous broad X-ray radiation observed earlier from its active state (Bachetti et al. 2014). This more compelling argument in somehow or otherwise implies the luminosity $\sim 100$ times if compared to the Eddington limit. Such a colimation ($\sim 100$), which is comparable to that obtained for black holes (e.g., Ohsuga et al. 2007; Sadowski & Narayan 2013), would be needed to explain M82X-2 as beamed radiation from neutron star. 3) Equally noteworthy that the centroid of the persistent X-ray emission is between M82X-2 and M82X-1. If M82X-1 is indeed harbors plausible IMBH, (e.g. Patruno et al. 2006; Portegies et al. 2007; Roberts 2007; Casella et al. 2008; Feng & Kaaret 2010; Feng & Soria 2011; Pasham et al. 2014), we expect the similarity of the persistent X-ray properties of the M82X-1 and M82X-2 to imply that the non-pulsed emission from the latter originates in the accretion disc, as it must in the black hole M82X-1. In this sense, the NuSTAR discovery is unexpected and still hard to be explained in the context of magnetic neutron star pulsar model. The fraction of ULXs powered by neutron stars must be considered highly uncertain and many details of this scenario remain poorly understood. Added to this was the fact that NuSTAR finding may indeed not be rare in the ULX population. In the future astronomers also will look at more ULXs, and it is a matter of time until they could prove an expected ubiquitous feature of even more energetic ULX pulsations, as being common phenomena in the Universe. If confirmed, this would support a scenario in which the more ULXs beat with the pulse of black holes rather than magnetized neutron star systems. What if NuSTAR detection might radically change one's view of Nature. With this perspective in sight, it is wise in the case of M82X-2 to place constraints on the likelihood of the magnetic neutron star pulsar systems, so the model of common pulsar will be tested critically.

1.3. Result

Putting apart the discussion of inherent problems of the mass scaling of the black holes in ULXs, which is beyond the scope of this report, we approach the M82X-2 issue from the standpoint of black holes rather than magnetic neutron star pulsar systems. To reconcile the observed unusual high pulsed luminosity with the above mentioned violation of the Eddington limit, we examine the physics which is at work in ultraluminous pulsations by assuming that M82X-2 is being a spinning intermediate-mass black hole (SIMBH). If a black hole of intermediate mass will be an exact law of Nature, it is certainly an attractive scenario. For example, Kong et al. (2007) suggest that the M82X-2 is a binary system with a black hole accretor. Assuming the persistent emission is isotropic, the X-ray luminosity $\sim 10^{40} \text{erg s}^{-1}$ implies that the compact object is a $> 100 M_\odot$ IMBH in the low/hard state. However, one may be tempted to argue truly that most of the issues and objections raised above cannot be solved in the framework of conventional black hole models, to which we refer as phenomenological black hole models (PBHMs) (see subsect.2.1). The coherent periodicity obviously rules out PBHMs, because 1) black holes do not radiate; 2) the spinning black holes are axisymmetric and have no internal structure on which to attach a periodic emitter. Orbital motion, whether modulating some emission mechanism directly or exciting short-period pulsations, would decay very quickly due to gravitational radiation. With this in mind, we revisited the MTBH which completes PBHM by exploring the most important processes of spontaneous breaking of gravitation gauge symmetry and rearrangement of vacuum state at huge energies. One of the purposes of this report is to motivate and justify the further implications of MTBH framework to circumvent the alluded obstacles without the need for significant breaking of Eddington limit. We will proceed according to the following structure. To start with, some latest developments on IMBHs are discussed in subsection 1.4. We provide an
analysis aimed at clarifying the current situation. To make the rest of paper understandable, section 2 deals with a brief review of key objectives of the MTBH framework, in particular, in relevance to IMBH seeds as a guiding principle. In section 3 we set out to examine the ultraluminous pulsations powered by M82X-2, constituting mass-exchange binary with the O/B-type donor star. We discuss a basic geometry which describes the rotating axisymmetric black holes and bring some observations which comprise the whole of the case. We derive a general profile of pulsed luminosity of M82X-2, give a quantitative account of a potential dynamical mass scaling of M82X-2 and other energetics, estimate the mass of companion and the orbit parameters of the mass-exchange binary, discuss the measured spin-up rate, and calculate the torque added to M82X-2 per unit mass of accreted matter. Concluding remarks are presented in section 4.

1.4. Some latest developments on IMBHs

Transient behavior of M82X-2 with a massive companion donor star likely requires an IMBH, even though the physical interpretation of the latter is still controversial. If IMBHs exist they have important implications for the dynamics of stellar clusters and the formation of supermassive black holes. These objects are of particular interest because this population would fall within the gap between the two principal black hole populations, i.e. super-massive black holes (SMBHs), with masses of $10^6 - 10^{10} M_{\odot}$, and stellar mass black holes, with masses of $\sim 10 M_{\odot}$. A ROSAT/HRI catalog of ULXs (Colbert & Mushotzky 1999) provides a clue to fill in the missing population of the IMBHs. Currently there are very few well studied IMBHs, two examples are NGC 4395 (Felippenko & Ho 2003) and POX 52 (Kunth et al. 1987; Barth et al. 2004). The IMBHs have non-standard spectra, which show a cutoff at a few keV (Stobbart et al. 2006). Note that other black holes, stellar as well as super-massive, at a few per cent of Eddington luminosity have hard power-law-like spectra (Zdziarski et al. 1997). Some ULXs show a harder, 14 keV thermal component with the corresponding radius of only 3040 km (Makishima et al. 2006) (Stobbart et al. 2006). It is not clear to date how IMBHs would form. They have remained observationally elusive, with dynamical evidence for such objects in large globular clusters still the subject of some dispute. On the one hand, to produce an massive IMBH of $10^2 - 10^4 M_{\odot}$, the core collapse of an isolated star in the current epoch is not a viable process, which is how the stellar black holes are thought to form, because of the lack of very massive stars. Their environments lack the extreme conditions, i.e. high density and velocities observed at the centers of galaxies, which seemingly lead to the formation of supermassive black holes. There are two conventional scenarios for the formation of IMBHs. The first is the merging of stellar black holes and other compact objects by means of gravitational radiation. The second one is the runaway collision of massive stars in dense stellar clusters and the collapse of the collision product into an IMBH. But, in fact, most ULX host galaxies do not even have stellar clusters sufficiently massive and compact to satisfy the requirements for runaway core collapse. These objects could be formed inside clusters that have since dispersed. However, the evaporation timescale of such clusters would be too long to explain the observed association of many ULXs with young ($\leq 20$ Myr) stellar populations. For example, one of the strongest candidates for IMBH to date is the hyperluminous X-ray source HLX1 or 2XMM J011028.1-460421, possibly located in the galaxy ESO243-49, or, at least, projected inside the $\mu_B = 25.0$ mag arcsec$^{-2}$ surface brightness isophote of that galaxy (Farrell et al. 2009; Godet et al. 2009; Soria et al. 2010) report a discovery of the likely optical counterpart to this source. In their analysis of the UV emission in ESO243-49, they determine the optical flux, and the X-ray/optical flux ratio, and conclude that the X-ray source belongs to ESO243-49, seemingly located inside a massive star cluster. A metal-free population III stars formed in the very early Universe could reach masses of a few hundred $M_{\odot}$, above the pair-instability limit, and thus may have collapsed into IMBHs (Madau & Rees 2001). It was then expected that in young and dense star clusters, dynamical friction could lead to massive stars sinking towards the center and undergoing runaway collisions and mergers on timescales $10^6$ yr. Dynamical evidence for IMBHs with masses $\sim 10^4 M_{\odot}$ has been proposed for a few globular clusters, e.g., G1 in M31 at the 1.5$\sigma$ significance level (Gebhardt et al. 2003).
2005), although the issue is still controversial, and these results require further extensive and careful investigation of the stellar density and velocity distributions in globulars, being of the highest importance in understanding of the formation of IMBHs (Anderson, & van der Marel 2010). In massive and/or compact globular clusters, a central seed black hole may grow by up to a factor of 100 via accretion of gas lost by the first generation of cluster stars in their red-giant phase (Vesperini et al. 2010); or, IMBHs may wander in the halo of major galaxies, after tidal stripping of merging satellite dwarfs that contained nuclear BHs (King & Dehnen 2005, Bellovary et al. 2010). Although this seems one of the most plausible explanations for the above mentioned source HLX-1, in general, currently we do not have a complete theoretical interpretation of physical nature of growth of black hole seeds. Therefore, the MTBH framework may become of eminent physical significance in tackling this problem.

2. MTBH, Revisited: the implications for IMBHs

The aim of the present section is to recount some of the highlights behind the MTBH for the benefit of the reader, as a guiding principle to make the rest of paper understandable. We shall see how a IMBH seed is thought to form. There are several important topics not touched upon here, which will eventually benefit from a proposed gravitation theory. Although some key theoretical ideas were introduced with a satisfactory substantiation, we have also attempted to maintain a balance being overly detailed and overly schematic.

2.1. Phenomenological model of black holes

From its historical development, up to current interests, the efforts in the active galactic nuclei (AGN) physics have evoked the study of a major unsolved problem of how efficiently such huge energies observed can be generated. This energy scale severely challenges conventional source models. The huge energy release from compact regions of AGNs requires extremely high efficiency (typically $\geq 10$ per cent) of conversion of rest mass to other forms of energy. This led early on to suggestions that AGNs are powered by SMBHs, with masses of $10^6 - 10^{10} M_\odot$. A complex study of AGN evolution requires a comprehensive understanding of a new field of astrophysics, so-called black hole demography. This studies the important phenomena of the birth and growth of black holes, the merging of stellar mass black holes and their evolutionary connection to other objects in the Universe. These ideas gather support especially from a breakthrough made in recent observational and computational efforts on understanding of coevolution of black holes and their host galaxies, particularly through self-regulated growth and feedback from accretion-powered outflows (e.g. Natarajan & Treister 2009; Vestroegaard 2004; Volonteri et al. 2008; Volonteri & Natarajan 2009; Volonteri et al. 2010; Shankar et al. 2009; Kelly et al. 2010; Natarajan 2011; Treister & Megan 2012; Willott et al. 2010; Devecchi & Volonteri 2009). In these models, at early times the properties of the assembling SMBH seeds are more tightly coupled to properties of the dark matter halo as their growth is driven by the merger history of halos.

General relativity (GR) has stood the test of time and can claim remarkable success, although there are serious problems concerning the role of singularities or black holes. This state of affairs has not much changed up to present and proposed abundant models are not conducive to provide non-artificial and unique recipe for resolving controversial problems of energy-momentum conservation laws of gravitational interacting fields, localization of energy of gravitational waves and also severe problems involved in quantum gravity. A tacit assumption of theoretical interpretation of aforementioned astrophysical scenarios is a general belief (e.g. Rees 1984; Shapiro 2005; Munyaneza & Biermann 2006; Alexander & Natarajan 2014 and references therein) reinforced by statements in textbooks, that a longstanding standard PBHM can describe the growth of accreting black hole seeds. In the framework of GR, the PBHM implies the most general Kerr-Newman black hole model, with the integral parameters of total mass ($M$), angular momentum ($J$) and charge ($Q$), still has to put in by hand. But such beliefs are suspect and should be critically re-examined. Even though being among the most significant advances in as-
trophysics, it is rather surprising that PBHM is routinely used to explore this problem as though it cannot be accepted as convincing model for addressing the black hole growth, because in this framework the very source of gravitational field of the black hole is a kind of meaningless curvature singularity at the center of the stationary black hole, which is hidden behind the event horizon. The theory breaks down inside the event horizon which is causally disconnected from the exterior world. Either the Kruskal continuation of the Schwarzschild \((J = 0, Q = 0)\) metric, or the Kerr \((Q = 0)\) metric, or the Reissner-Nordstrom \((J = 0)\) metric, show that the static observers fail to exist inside the horizon. Any object that collapses to form a black hole will go on to collapse to a singularity inside the black hole. Any timelike worldline must strike the central singularity which wholly absorbs the infalling matter. Therefore, the ultimate fate of collapsing matter once it has crossed the black hole surface is unknown. So, one should deliberately forebear from presumption of exotic hypothetical growth behavior of black holes, which seems nowhere near true if one applies the phenomenological model. This ultimately cannot accumulate matter in the central part and, thus, neither the growth of black holes nor the increase of their mass-energy density could occur at accretion of outside matter, or by means of merger processes. Yet it is still thought provoking how can one be sure that some hitherto unknown source of pressure does not become important at huge energies and halt the infinite collapse. That in PBHM there is no provision for growth behavior of black holes, is because in it one assigned only an insufficient attribute to this. The PBHM is a rather restricted model and one needs to realise that if one can gain insight into exploring a new process of spontaneous breaking of gravitation at huge energies, one has then made room for growth and merging behavior of black holes. To fill the void which the standard PBHM presents, thus, one plausible idea to innovate the solution to alluded key problems would appear to be such breaking mechanism, and thereof for that of rearrangement of vacuum state itself.

2.2. Proposed gravitation theory

In this subsection we present a brief outline of the key ideas of the underlying theory, which yields the gravitational interaction at huge energies drastically different from earlier suggested schemes. This theory involves a drastic revision of a role of local internal symmetries in physical concept of curved geometry, and explores the most important processes of spontaneous breaking of gravitation gauge symmetry and rearrangement of vacuum state. It was originally proposed by (Ter-Kazarian (1997, 2001 2010 and references therein), and thoroughly discussed in (Ter-Kazarian 2014 2015a). This extension, suitable for applications in extremely high energy astrophysics, is a bold assumption in its own right. In its present formulation, this theory exploits the language of the fundamental geometric structure- distortion gauge induced fiber-bundle, which provides a modified gravitational theory, as a corollary of the spacetime deformation/distortion framework, suggested by (Ter-Kazarian 2015a) (see also Ter-Kazarian (2011 2015b)). It should be emphasized, that the standard Riemannian (and its extensions) space interacting quantum field theory cannot be a satisfactory ground for addressing the problems in quest. The difficulties associated with this step are notorious, however, these difficulties are technical. In the main, they stem from the fact that Riemannian geometry, in general, does not admit a group of isometries, and that it is impossible to define energy-momentum as Noether local currents related to exact symmetries. This, in turn, posed severe problem of non-uniqueness of the physical vacuum and the associated Fock space. A definition of positive frequency modes cannot, in general, be unambiguously fixed in the past and future, which leads to \(|in > \neq |out >\), because the state \(|in >\) is unstable against decay into many particle \(|out >\) states due to interaction processes allowed by lack of Poincaré invariance. A non-trivial Bogolubov transformation between past and future positive frequency modes implies that particles are created from the vacuum and this is one of the reasons for \(|in > \neq |out >\). Keeping in mind aforesaid, we develop on the framework of the general gauge principle, as from first principles: We consider the principal fiber bundle with the semi-Riemannian spacetime,
$V_4$, as the base space, and with the structure group, $G_{V}$, generated by the hidden local internal symmetry of two-parameter abelian local group $U^{loc}(2) = U(1)_{Y} \times U(1) = U(1)_{Y} \times \text{diag}(SU(2))$. This group is implemented on the flat space, $M_4$. The collection of matter fields of arbitrary spins take values in standard fiber. To involve a drastic revision of the role of gauge fields in the physical concept of the spacetime deformation/distortion, we generalize the standard gauge scheme via the concept of distortion gauge field which acts on the external spacetime groups. The group $U^{loc}(2)$ has two generators, the third component $T^i$ of isospin $\vec{T}$ related to the Pauli spin matrix $\vec{\tau}$, and hypercharge $Y$ implying $Q^d = T^3 + \frac{1}{2} Y$, where $Q^d$ is the distortion charge operator assigning the number -1 to particles, but +1 to anti-particles. We connect the structure group $G_{V}$, further, to the non-linear realization of the Lie group $G_D$ of distortion of the spacetime (e.g. Ter-Kazarian (2014, 2015a)), i.e. we extend the curvature of the spacetime continuum to general distortion as the theory of spontaneous breaking of distortion symmetry. This can be achieved by non-linear realizations of the distortion group $G_D$. The non-linear realization technique or the method of phenomenological Lagrangians (Coleman et al. 1967; Callan et al. 1969; Salam & Strathdee 1969; Isham et al. 1971; Ogievetsky 2009; Volkov 2010; Weinberg 2010) provides a way to determine the transformation properties of fields defined on the quotient space. In accord, we treat the distortion group $G_D$ and its stationary subgroup $H = SO(3)$, respectively, as the dynamical group and its algebraic subgroup. The fundamental field is distortion gauge field and, thus, all the fundamental gravitational structures in fact - the metric as much as the coframes and connections - acquire a distortion-gauge induced theoretical interpretation. We study the geometrical structure of the space of parameters in terms of Cartan’s calculus of exterior forms and derive the Maurer-Cartan structure equations. There is a reciprocity, treated in the Maurer-Cartan nonlinear structure equations, between the formal mathematical structure of distortion fields on the one hand, and the Goldstone fields, on the other. The group $U^{loc}(2)$ entails two neutral gauge bosons of $U(1)$, or that coupled to $T^3$, and of $U(1)_Y$, or that coupled to the hypercharge $Y$. Spontaneous symmetry breaking can be achieved by introducing the neutral complex scalar Higgs field. Minimization of the vacuum energy fixes the non-vanishing vacuum expectation value, which spontaneously breaks the theory, leaving the $U(1)_d$ subgroup intact, i.e. leaving one Goldstone boson. Consequently, the left Goldstone boson is gauged away from the scalar sector, but it essentially reappears in the gauge sector providing the longitudinally polarized spin state of one of gauge bosons that acquires mass through its coupling to Higgs scalar. Thus, the two neutral gauge bosons were mixed to form two physical orthogonal states of the massless component of distortion field, $(a) \ (M_a = 0)$, which is responsible for gravitational interactions, and its massive component, $(\bar{a}) \ (M_{\bar{a}} \neq 0)$, which is responsible for the, so-called inner distortion (ID)-regime. Hence, a substantial change of the properties of the spacetime continuum besides the curvature may arise at huge energies. This theory is renormalizable, because gauge invariance gives conservation of charge, also ensures the cancelation of quantum corrections that would otherwise result in infinitely large amplitudes. Without careful thought we expect that in this framework the renormalizability of the theory will not be spoiled in curved space-time as well, because, the infinities arise from ultra-violet properties of Feynman integrals in momentum space which, in coordinate space, are short distance properties, and locally (over short distances) all the curved spaces look like maximally symmetric (flat) space.

For brevity, we will not be further concerned with the actual details of this comprehensive theoretical framework, but only use it as a backdrop to validate the theory with more observational tests. For details, the interested reader is invited to consult the original papers. Discussed gravitation theory is consistent with GR up to the limit of neutron stars. But MTBH manifests its virtues application to the physics at huge energies. Whereas a significant change of properties of spacetime continuum, ID-regime (at $\bar{a} \neq 0$), arises simultaneously with the strong gravity ($a \neq 0$). The Compton length of the ID-field $\bar{a}(r)$ is $\lambda_{\bar{a}} = \frac{h}{m_{\bar{a}} c} \simeq 0.4 \text{fm}$. 
2.3. Crossing event horizon from inside the black hole

Let us to discuss in more details some principle issues in use. Recall that according to GR, the event horizon is impenetrable barrier for crossing from inside the black hole because of a singularity arisen at the Schwarzschild radius (radius of a non-rotating black hole) \( R_g = 2GM/c^2 = 2.95 \times 10^5 M/M_\odot \text{ cm} \). But in the framework of MTBH, this barrier disappears when a matter found in the ID-region of space-time continuum has undergone phase transition of II-kind and, thus, it transformed to proto-matter. To obtain some feeling about this phenomena, below we give more detailed explanation. In the framework of MTBH, we are led to construct a formalism of unitary mapping of the fields and their dynamics from \( M_4 \) to \( V_4 \), and vice versa. The field equations follow at once from the total gauge invariant Lagrangian in terms of Euler-Lagrange variations, respectively on both \( V_4 \) and \( M_4 \) spaces \cite{Ter-Kazarian2014, Ter-Kazarian2015}. The Lagrangian of distortion gauge field defined on the flat space is undifferentiated Killing form on the Lie algebra of the group \( U^{10c}(2) \) in adjoint representation, which yields the equation of distortion field. In the reminder of this subsection the quantities referred to \( V_4 \) are denoted by wiggles, and left without wiggles if they correspond to \( M_4 \). We are interested in the case of a spherical-symmetric gravitational field \( a_0(r) \) in presence of one-dimensional space-like ID-field \( \tilde{a} \). In the case at hand, one has the group of motions \( SO(3) \) with 2D space-like orbits \( S^2 \) where the standard coordinates are \( \tilde{\theta} \) and \( \tilde{\varphi} \). The stationary subgroup of \( SO(3) \) acts isotropically upon the tangent space at the point of sphere \( S^2 \) of radius \( \tilde{r} \). So, the bundle \( p : V_4 \to \tilde{R}^2 \) has the fiber \( S^2 = p^{-1}(\tilde{x}), \quad \tilde{x} \in V_4 \) with a trivial connection on it, where \( \tilde{R}^2 \) is the quotient-space \( V_4/SO(3) \). Considering the equilibrium configurations of degenerate barionic matter, we assume an absence of transversal stresses and the transference of masses in \( V_4 \)

\[
T^1_1 = T^2_2 = T^3_3 = -\tilde{P}(\tilde{r}), \quad T^0_0 = -\tilde{\rho}(\tilde{r}),
\]

where \( \tilde{P}(\tilde{r}) \) and \( \tilde{\rho}(\tilde{r}) \) \( (\tilde{r} \in \tilde{R}^2) \) are taken to denote the internal pressure and macroscopic density of energy defined in proper frame of reference that is being used. The equations of gravitation \((a_0)\) and ID \((\tilde{a})\) fields can be obtained in Feynman gauge \cite{Ter-Kazarian2001} as

\[
\Delta a_0 = \frac{1}{2} \left\{ \tilde{g}_{00} \frac{\partial^2}{\partial a_0^2} \tilde{\rho}(\tilde{r}) - \left[ \tilde{g}_{33} \frac{\partial^2}{\partial a_0^2} + \tilde{g}_{11} \frac{\partial^2}{\partial a_0^2} + \tilde{g}_{22} \frac{\partial^2}{\partial a_0^2} \right] \tilde{P}(\tilde{r}) \right\},
\]

\[
(\Delta - \lambda^2) \tilde{a} = \frac{1}{2} \left\{ \tilde{g}_{00} \frac{\partial^2}{\partial a_0^2} \tilde{\rho}(\tilde{r}) - \left[ \tilde{g}_{33} \frac{\partial^2}{\partial a_0^2} + \tilde{g}_{11} \frac{\partial^2}{\partial a_0^2} + \tilde{g}_{22} \frac{\partial^2}{\partial a_0^2} \right] \tilde{P}(\tilde{r}) \right\},
\]

where a diffeomorphism \( \tilde{r}(r) : M_4 \to V_4 \) is given \( r = \tilde{r} - R_g/4 \). A distortion of the basis \( \tilde{c} \) in the ID regime, in turn, yields the transformations of Poincaré generators of translations. Given an explicit form of distorted basis vectors, it is straightforward to derive the laws of phase transition for individual particle found in the ID-region \( (x_0 = ax_0 = 0, \; \tilde{x} = ax\tilde{a} \neq 0) \) of the space-time continuum, where a coupling constant \( \alpha \) relates to Newton gravitational constant \( G \) as \( \alpha^2 = 8\pi G/c^4 \). The Poincaré generators \( P_\mu \) of translations undergone following transformations \cite{Ter-Kazarian2001, Ter-Kazarian2015}:

\[
\tilde{E} = E, \quad \tilde{P}_{1,2} = P_{1,2} \cos \tilde{\theta}_3, \quad \tilde{P}_3 = P_3 - \tan \tilde{\theta}_3 \frac{m}{\cos \tilde{\theta}_3}, \quad \tilde{m} = \left( m - \tan \tilde{\theta}_3 \frac{m}{\cos \tilde{\theta}_3} \right)^2 + \sin^2 \tilde{\theta}_3 \frac{P^2 + P_3^2}{c^2} - \tan^2 \tilde{\theta}_3 \frac{E^2}{c^2},
\]

where \( E, P, m \) and \( \tilde{E}, \tilde{P}, \tilde{m} \) are ordinary and distorted energy, momentum and mass at rest, \( \tan \tilde{\theta}_3 = -\tilde{x} \). Hence the matter found in the ID-region \( (\tilde{a} \neq 0) \) of space-time continuum has undergone phase transition of II-kind, i.e., each particle goes off from the mass shell - a shift of mass and energy-momentum spectra occurs upwards along the energy scale. The matter in this state is called \textit{proto-matter} with the thermodynamics differed drastically from the thermodynamics of ordinary compressed matter. The resulting deformed metric on \( V_4 \) in holonomic coordinate basis takes the form

\[
\tilde{g}_{00} = (1 - x_0^2 + \tilde{x}^2), \quad \tilde{g}_{\mu\nu} = 0 \quad (\mu \neq \nu),
\]

\[
\tilde{g}_{33} = - [(1 + x_0^2 + \tilde{x}^2)], \quad \tilde{g}_{11} = -\tilde{r}^2, \quad \tilde{g}_{22} = -\tilde{r}^2 \sin^2 \tilde{\theta}.
\]
The metric (4) clearly shows that: a singularity at intersection of proto-matter disk with the event horizon (at $x_0 = 1$) disappears where a massive component of ID-field is not zero ($x \neq 0$), and hence the crossing event horizon from inside of black hole at such conditions is allowed.

2.4. Rational

Consisting of the proto-matter core and the outer layers of ordinary matter, the SPC configuration is the spherical-symmetric distribution of baryonic matter in many-phase stratified states. A layering is a consequence of the onset of different regimes in equation of state. Each configuration is defined by the two free parameters of central values of particle concentration $\bar{n}(0)$ and dimensionless potential of space-like ID-field $\bar{x}(0)$. The interior gravitational potential $x_0^{\text{int}}(r)$ matches into the exterior one $x_0^{\text{ext}}(r)$ at the surface of the configuration. The central value of the gravitational potential $x_0(0)$ can be found by reiterating integrations when the sewing condition of the interior and exterior potentials holds. The simulations confirm in brief the following scenario. The energy density and internal pressure have sharply increased in proto-matter core, with respect to corresponding central values of neutron star, proportional to gravitational forces of compression. This counteracts the collapse and equilibrium holds even for the masses up to $\sim 10^{10}M_\odot$. Encapsulated in a complete set of equations of SPC-configuration, the SPC is a robust structure that has stood the tests of the most rigorous theoretical scrutinies of its stability, which was a central issue in [Ter-Kazarian et al. 2007]. Minimizing the total energy gives the equilibrium configurations. The second derivative of total energy gives stability information. Although a relativity tends to destabilize configurations, however, a numerical integrations of the stability equations of SPC clearly proves the stability of resulting cores. Due to it, the stable equilibrium holds as well in outward layers and, thus, an accumulation of matter is now allowed around the stable SPC. To emphasize the distinction between phenomenological and microscopic black hole models, we present their schematic plots in Fig. 1 to guide the eye. One of the most remarkable drawback of MTBH is that the central singularity cannot occur, which is replaced by finite though unbelievably extreme conditions held in the stable SPC where, nevertheless, static observers are existed. The SPC is always found inside the event horizon sphere, therefore it could be observed only in presence of accreting matter. The SPC surrounded by the accretion disk presents the microscopic model of AGN. The SPC accommodates the highest energy scale up to hundreds ZeV in central proto-matter core of supermassive black holes, which accounts for the spectral distribution of the resulting radiation of galactic nuclei. An external physics of accretion onto the black hole in the earlier half of its lifetime is identical to the processes in Schwarzschild’s model. A crucial difference in the model context between the phenomenological and microscopic black holes comes in when one looks for the spontaneous breaking of gravitation gauge symmetry at huge energies, and thereof making room for growth and merging behavior of black holes. We have shown that the AGN evolution and black hole growth, when properly analysed, agree with our claims.

![Fig. 1.— Left panel: Phenomenological model of non-spinning black hole. The meaningless singularity occurs at the center inside the black hole. Right panel: Microscopic model of non-spinning black hole, with the central stable SPC. An infalling matter with the time forms PD around the SPC. In final stage of growth, a PD has reached out the edge of the event horizon. Whereas a metric singularity inevitably disappears and UHE neutrinos may escape from event horizon to outside world through vista, i.e. a thin belt area $S = 2\pi R_g d$ of intersection of proto-matter disk with the event horizon, with opening angle $\theta_\nu$. Accepted notations: EH=Event Horizon, AD=Accretion Disk, SPC=Superdense Proto-matter Core, PD=Proto-matter Disk.](image)
2.5. The intermediate mass, pre-radiation time and initial redshift of seed black hole

We argue that in the framework of MTBH, the black hole seeds might grow driven by the accretion of outside matter when they were getting most of their masses. An infalling matter with time forms a thin proto-matter disk around the proto-matter core tapering off faster at reaching out the event horizon. As a metric singularity inevitably disappears and the ZeV-neutrinos, produced via simple or modified URCA processes in deep layers of SPC and proto-matter disk, may escape from event horizon to outside world through a thin belt area \( S = 2\pi R_g d \), even after the strong neutrino trapping. The thickness of proto-matter disk at the edge of event horizon is denoted by \( d \). The neutrinos are collimated in very small opening angle \( \theta_\nu \approx \varepsilon_d = \frac{d}{2R_g} \ll 1 \). The trapping is due to the fact that as the neutrinos are formed in proto-matter medium at super-high densities they experience greater difficulty escaping from it before being dragged along with the matter, i.e. the neutrinos are trapped comove with matter. In this framework we introduced a notion of pre-radiation time (PRT) of black hole which is referred to as a lapse of time \( T_{BH} \) from the birth of black hole till neutrino trapping - provision for the earlier half of the lifetime of black hole:

\[
T_{BH} = \frac{M_d}{\dot{M}}. \tag{5}
\]

Here \( M_d \) is the mass of proto-matter disk, \( \dot{M} \) is an appropriately averaged mass accretion rate. To render our discussion here a bit more transparent, we present the relation between typical PRT versus bolometric luminosity of supermassive black holes as follows:

\[
T_{BH} \approx 0.32 \frac{R_d}{r_{OV}} \left( \frac{M_{BH}}{M_\odot} \right)^2 \frac{10^{39} \text{W}}{L_{\text{bot}}} \text{ yr}, \tag{6}
\]

where \( R_d \) is the radius of the proto-matter core, \( r_{OV} = 13.68 \text{ km} \). At times \( > T_{BH} \), the black hole no longer holds as a region of spacetime that cannot communicate with the external Universe. In this framework, we computed the fluxes of ZeV-neutrinos from plausible accreting supermassive black holes closely linking with the 377 AGNs (Ter-Kazarian 2014, 2015a). In accord, the AGNs are favored as promising pure neutrino sources because the computed neutrino fluxes are highly beamed along the plane of accretion disk, and peaked at high energies and collimated in very small opening angle \( \theta_\nu \approx \varepsilon_d \ll 1 \). While hard to detect, the extragalactic ZeV-neutrinos may reveal clues on the puzzle of the origin of ultra-high energy cosmic rays, as they have the advantage of representing unique fingerprints of hadron interactions and, therefore, can initiate the cascades of UHE-particles with energies exceeding \( 1.0 \times 10^{20} \text{ eV} \) (comprehensive reviews can be found in [Castellina & Donato 2012; Letessier-Selvon & Stanev 2011; Sigl 2011; Kotera & Olinto 2010; Semikoz 2010]).

Consequently, we have studied a growth of proto-matter disk and derived the mass of black hole seed (Ter-Kazarian 2015a) - provision for the second half of the lifetime of black hole:

\[
\frac{M_{BH}}{M_\odot} = \frac{M_{BH}}{M_\odot} \left( 1 - 2.305 \frac{R_d}{r_{OV}} \frac{M_{BH}}{M_\odot} \right), \tag{7}
\]

and initial redshift

\[
z_{\text{Seed}} \approx z + H_0 T_{BH}, \tag{8}
\]

where \( H_0 \) is the Hubble’s constant. Whereas interpreting the redshift as a cosmological Doppler effect, and that the Hubble law could most easily be understood in terms of expansion of the Universe, as a further consistency check, we then turned the problem around by asking the purely academic question of principle what could be the initial redshift, \( z_{\text{Seed}} \), of seed black hole if the mass, the luminosity and the redshift, \( z \), of black hole at present time are known. Equation (7) holds at \( \frac{R_d}{r_{OV}} \lesssim 0.023 \frac{R_g}{r_{OV}} \), where \( R_g \) is the gravitational radius of black hole seed. We have undertaken a large series of numerical simulations with the goal to trace an evolution of the mass assembly history of 377 accreting supermassive black hole seeds in AGNs to the present time and examine the observable signatures today. Given the redshifts, masses and luminosities of these black holes at present time collected from the literature, we compute the
initial redshifts and masses of the corresponding black hole seeds.

Having gained some insight into the supermassive black hole physics, let us now comment briefly on the implications for IMBHs. Equation (7) shows that the seed of IMBH can be formed in the stellar mass black hole region if the condition

$$\frac{R_d}{r_{OV}} \leq 0.434 \frac{M_\odot}{M_{BH}} \left(1 - \frac{M_\odot}{M_{BH}}\right)$$

holds. A creation of IMBHs may be possible in the young stellar populations that we generally find ULXs co-habiting with. The IMBH with mass, say $M_{BH} \approx 1.0 \times 10^4 M_\odot$, may originate from the seed with stellar mass of $\sim 1 M_\odot$ at $R_d/r_{OV} \approx 4.3 \times 10^{-4}$, and will reach to the final state after a lapse of growing time of order $T_{BH} \approx M_{BH}/\dot{M}$.

3. The mass-exchange binary containing M82X-2

As in the case of neutron stars, we expect that accreting black holes are fast spinning objects. For the self-contained arguments, we need to extend the preceding algorithm of non-spinning MBHM to its spinning counterpart, which is almost a matter of routine, to change the geometry of static SPC to a more general one, describing axisymmetric rotating SPC. For the standard calculations of rapidly rotating relativistic bodies in astrophysics, reader may refer to e.g. Carter (1970); Bardeen (1970); Komatsu et al. (1989); Cook et al. (1992, 1994); Bonazzola et al. (1993); Bonazzola & Gourgoulhon (1994); Stergioulas (2003) and references therein.

3.1. The geometry of rotating axisymmetric SPC

In this subsection we will collect together the results which are required later. The non-spinning SPC is static and spherically symmetric. So, one needs to be clear about more general geometry which can describe rotating axisymmetric SPCs. The principle foundation of the spinning configurations first comprises the following additional distinctive features with respect to non-spinning ones: 1) Rapid rotation causes the shape of the SPC to be flattened by centrifugal forces-flattened at poles and bulged at equator (oblate spheroid, which is second order effect in the rotation rate). 2) A rotating massive SPC drags the space and time around with it. The local inertial frames are dragged by the rotation of the gravitational field, i.e. a gyroscope orbiting near the SPC will be dragged along with the rapidly rotating SPC. This is probably the most remarkable feature that could serve as a link with the general description of spacetime (also see Ter-Kazarian (2012)). Beside the geodetic process, a spin of the body produces in addition the Lense-Thirring procession.

To look into the future, measurement of the gravitationnal ratio of particle would be a further step, see e.g. Ni (2010) and references therein, towards probing the microscopic origin of gravity. Let the world coordinate $t (= x^0)$ be the time (in units of $c$), and $\phi (= x^1)$ be the azimuthal angle about the axis of symmetry. Moreover, a metric of a two-space with positive or negative signature, $(x^2, x^3)$, can always be brought to the diagonal form by a more coordinate transformation. Since the source of gravitational field has motions that are pure rotational about the axis of symmetry, then the energy-momentum tensor as the source of the metric will have the same symmetry. Namely, the space $M_4$ would be invariant against simultaneous inversion of time $t$ and azimuthal angle $\phi$. The $3 + 1$ formalism is the most commonly used approach in which, as usual, spacetime is decomposed into the one parameter family of space-like slices - the hypersurfaces $\Sigma_t$. The study of a dragging effect is assisted by incorporating with the soldering tools in order to relate local Lorentz symmetry to curved spacetime. These are the linear frames and forms in tangent fiber-bundles to the external general smooth differential manifold, whose components are so-called tetrad (vierbein) fields. Whereas, the $M_4$ has at each point a tangent space, $T_x M_4$, spanned by the anholonomic orthonormal frame field, $e$, as a shorthand for the collection of the 4-tuplet $(e_0 = \exp(-\nu)(\partial_t + \omega \partial_\phi), e_1 = \exp(-\nu) \partial_\phi, e_2 = \exp(-\mu_2) \partial_2, e_3 = \exp(-\mu_3) \partial_3)$, where $e_a = e_a^\mu \partial_\mu$, $e_a^\mu$ is the the soldering form between the tangent space and the spacetime manifold. This is called a Bardeen observer, locally nonrotating observer, or the local Zero Angular-Momentum Observers (ZAMO), i.e. observers whose worldlines are normal to the hypersurfaces defined by constant coordinate time, $t = \text{const}$, also called Eulerian observers. Here we
use Greek alphabet \((\mu, \nu, \rho, \ldots = 0, 1, 2, 3)\) to denote the holonomic world indices related to \(\mathcal{M}_4\), and the first half of Latin alphabet \((a, b, c, \ldots = 0, 1, 2, 3)\) to denote the anholonomic indices related to the tangent space. The frame field, \(e_i\), then defines a dual vector, \(\vartheta_i\), of differential forms, \(\vartheta_i = \left(\begin{array}{c}
abla^0 = \exp \nu dt \\
abla^1 = \exp \psi (d\psi - \omega dt) \\
abla^2 = \exp \mu_2 dx^2 \\
abla^3 = \exp \mu_3 dx^3 \end{array}\right)\), as a shorthand for the collection of the \(\vartheta^b = e^b_{\mu} dx^\mu\), whose values at every point form the dual basis, such that \(e_a \cdot \vartheta^b = \delta_a^b\), where \(\cdot\) denoting the interior product, namely, this is a \(C^\infty\)-bilinear map \(\cdot : \Omega^1 \to \Omega^0\) with \(\Omega^0\) denotes the \(C^\infty\)-modulo of differential \(p\)-forms on \(\mathcal{M}_4\). In components \(e_a^b e^c_{\mu} = \delta_a^c\), the norm \(ds\) of infinitesimal displacement \(dx^\mu\) on \(\mathcal{M}_4\), describing the stationary and axisymmetric spacetimes, reads

\[ds = e \vartheta = e_\mu \otimes \vartheta^\mu \in \mathcal{M}_4.\]  

Therefore, the holonomic metric on the space \(\mathcal{M}_4\) can be recast into the form

\[g = g_{\mu\nu} \vartheta^\mu \otimes \vartheta^\nu = g(e_\mu, e_\nu) \vartheta^\mu \otimes \vartheta^\nu,\]

with the components \(g_{\mu\nu} = g(e_\mu, e_\nu)\) in dual holonomic basis \(\{\vartheta^\mu \equiv dx^\mu\}\). That is

\[ds^2 = -\exp(2\nu)dt^2 + \exp(2\psi)(d\phi - \omega dt)^2 + \exp(2\mu_2)(dx^2)^2 + \exp(2\mu_3)(dx^3)^2,\]

where the five quantities \(\nu, \psi, \omega, \mu_2\) and \(\mu_3\) are only functions of the coordinate \(x^2\) and \(x^3\). In these case at hand, the metric function \(\omega\) is the angular velocity of the local ZAMO with respect to an observer at rest at infinity. Thereby the redshift factor \(\alpha \equiv \exp \nu\) is the time dilation factor between the proper time of the local ZAMO and coordinate time \(t\) along a radial coordinate line, i.e. the redshift factor for the time-slicing of a spacetime. In accord, all the geometrical objects are split into corresponding components with respect to this time-slice of spacetime. In particular, the splitting of manifold \(\mathcal{M}_4\) into a foliation of three-surfaces will induce a corresponding splitting of the affine connection, curvature and, thus, of the energy-momentum tensor which can as well be written in terms of the energy density \(E = T(n, n) = T_{\mu\nu} n^\mu n^\nu\) measured by an adapted Eulerian observer of four-velocity \(n^\mu\), the momentum flow \(J_a = -\gamma^\mu a T_{\mu\nu} n^\nu\) and the corresponding stress tensor \(S_{\alpha\beta} = \gamma^\mu a^\nu T_{\mu\nu} \left( S = S_{00}^0 \right)\), that is \(T_{0\beta} = E n^\beta + n^\alpha J^\beta + J^\beta n^\beta + S_{0\beta}\). Here \(n^\mu\) is the unit orthogonal vector to the hypersurface \(\Sigma_t\), whereas the spacetime metric \(g\) induces a first fundamental form with the spatial metric \(\gamma_{\alpha\beta}\) on each \(\Sigma_t\) as \(\gamma_{\alpha\beta} = g_{\alpha\beta} + n_\alpha n_\beta\). The form \(\gamma^\mu\) includes one gauge freedom for the coordinate choice. For the spherical type coordinates \(x^2 = \theta\) and \(x^3 = r\), for example, so-called quasi-isotropic gauge corresponds to \(\gamma_{r\theta} = 0\) and \(\gamma_{\theta\theta} = r^2 \gamma_{rr}\). Then, one may define the second fundamental form which associates with each vector tangent to \(\Sigma_t\), and the extrinsic curvature of the hypersurface \(\Sigma_t\) as minus the second fundamental form. Aftermath, one can define the usual Lorentz factor \(W = -n_{\mu} u^\mu = \alpha u^t\) for a perfect fluid with conventional stress-energy tensor \(T_{\mu\nu} = (\rho + P)u^\mu u^\nu + P g_{\mu\nu}\), where \(\rho\) is the energy density and \(P\) is the pressure. Hence \(E = W^2(\rho + P) - P\) and \(J^i = (E + P)u^i\), where the fluid three-velocity \(u^i (i = 1, 2, 3)\) implies \(u^t = W(u^i - \beta^i / \alpha)\). Thereby the resulting stress tensor can be written \(S_{ij} = (E + P)u^i u^j + P \delta_{ij}\). The four-velocity for rotating fluid reads \(u = u^t (\partial / \partial t) + \Omega \partial / \partial \phi\), where \(\Omega = \nu / u^t\) is the fluid angular velocity as seen by an inertial observer at rest at infinity. It is convenient to give the equations in the isotropic gauge, \(\exp(2\mu_2) = \exp(2\mu_3) = \exp(2\mu)\), in the cylindrical coordinates \(d\theta = dx^2\), \(dz = dx^3\), or in pseudospherical coordinates \(r d\theta = dx^2\) and \(dr = dx^3\), where the cylindrical radius is written \(\exp(\psi) = r \sin \theta\). The four-vector for rotating fluid reads \(u^- = u^t (\partial / \partial t) + \Omega (\partial / \partial \phi)\), where \(\mu\) denoting a function of \(r\) and \(\theta\) only. Therefore, the metric \(\gamma_{\mu\nu}\) becomes

\[ds^2 = -\exp(2\nu)dt^2 + B^2 r^2 \sin^2 \theta \exp(-2\nu)(d\phi - \omega dt)^2 + \exp(2\mu)(dr^2 + r^2 d\theta^2).\]

Consequently, the components of the energy-momentum tensor of matter with total density \(\rho\) and pressure \(P\) are given in the non-rotating anholonomic orthonormal frame as \(T^{ab} = e^a_{\mu} e^b_{\nu} T_{\mu\nu}\), \(T^{00} = W^2(\rho + PV^2)\), \(T^{11} = W^2(\rho + PV^2)\), \(T^{01} = W^2(\rho + P)V\) and \(T^{22} = T^{33} = P\), with its trace \(T = -\rho + 3P\), where \(V\) is the velocity (in units of \(c\)) with respect to the Bardeen observer \(V = \gamma_{\nu} (\nu - \omega)\), so \(W = \gamma_{\nu} / \gamma_{\nu} - \omega\). However, at this point we cut short and, in what follows,
we will refrain from providing further lengthy details of the mathematical apparatus of proposed gravitation theory at huge energies and rigorous solution of the extended equations describing the spinning MBHM, which is beyond the scope of this report. This entire set includes the gravitational and ID field equations of the time-slices generated by the above stress-energy tensor, the angular momentum equation with the momentum flow determining the frame-dragging potential, the hydrostatic equilibrium equation and the state equation specified for each domain of many layered spinning SPC- configurations. Theoretical evolutionary paths of this type which are suitable for rigorous comparison with the behavior of observed sources will be separate topic of comprehensive investigation elsewhere. But some evidence for a simplified physical picture, without loss of generality, is highlighted in the rest of this section where we extend preceding developments of MTBH in concise form, without going into the subtleties, as applied to the initially rigid-body spinning IMBH configuration of angular velocity $\Omega$.

3.2. The X-ray radiation from SIMBH

If this were the case, eventually the spinning proto-matter core and a thin co-spinning proto-matter disk driven by accretion would be formed. The evolution and structure of a proto-matter disk is largely determined by internal friction. Before tempting to build a physical model in quest, the other features of SIMBH configuration also need to be accounted which comprise the whole of the case. The fact that the rotational energy has a steeper dependence on the radius of the compact object than the internal energy in the relativistic limit is quite significant. Equilibrium can always be achieved for massive configurations with nonzero angular momentum by decreasing its radius. Also, there are two characteristic features that distinguish a spinning relativistic SPC-configuration from its non-spinning counterpart: 3) The geodetic effect, as in case of a gyroscope, leads an accretion stream to a tilting of its spin axis in the plain of the orbit. Hence a proto-matter disk will be tilted from the plane of accretion on a definite angle $\delta$ towards the equator. 4) Besides the UHE neutrinos, produced in the deep interior layers of superdense proto-matter medium as in case of non-spinning model, the additional ther-
nal diffuse blackbody radiation is released from the outer surface layers of ordinary matter of spinning SPC and co-spinning proto-matter thin disk. All of the rotational kinetic energy is dissipated as thermal blackbody radiation. This is due to the physical condition that these layers optically thick and, eventually, in earlier half of the lifetime of spinning black hole, at times $< T_{BH}$, the strict thermodynamic equilibrium prevails for this radiation because there would be no net flux to outside of event horizon in any direction. That is, the emission from the isothermal, optically thick outer layers at surface is blackbody, which is the most efficient radiation mechanism. This radiation is free of trapping. With this guidelines to follow, we may proceed in relatively simple way toward first look at some of the associated physics and can be quick to estimate the physical characteristics of mass-exchange X-ray binaries. Examining the pulsations revealed from M82X-2, as a working model we assume the source of the flashes to be a self-gravitating SIMBH resided in the final stage of growth. This implies that a thin co-spinning proto-matter disk has reached out the edge of the event horizon. Due to it a metric singularity inevitably disappears at the intersection of proto-matter disk with the event horizon. Hence, the crossing event horizon at such conditions from inside of black hole is allowed. This general behavior is very robust and depends very little on the details of the model of SPC. A principle physical properties of this phenomena for non-rotating SPC are already discussed in subsection 2.3. Without being carefully treated, even though these properties are of great significant for a rotating SPCs too. Actually, by virtue of subsection 3.1, they will retain for a more general geometry if metric (1) will appropriately be recast into (13) type, which describes a rotating axisymmetric SPCs. We conclude on the basis of these observations that the energy can be carried away to outside world by the thermal diffuse blackbody X-ray radiation through a thin belt area $S$. As M82X-2 spins, the pulse profile results from the axial tilt or obliquity. Hence the X-ray beams intercept Earth-like lighthouse beacons. The orbital motion causes a modulation in the observed pulse frequency. The SIMBH model of M82X-2 in binary system is schematically plotted in Fig. 2. No eclipse condition holds. The parameters of a binary system is viewed in the orbital plane.

3.3. Basic geometry: Implications on the pulse profile and mass scaling

To see where all this is leading to, let us consider next the real issue that of the physical description of M82X-2. A knowledge of the dynamical mass measurements of the compact objects that power ULXs is a primarily necessary prerequisite to the derivation of a complete picture about the physical nature of ULXs. Keeping in mind aforesaid, we are now in a position to derive a general pulse profile dependent upon the position angles, and give a quantitative account of a potential dynamical mass scaling of M82X-2 and other energetics. The most reliable method is to measure the mass function through the secondary mass and orbital parameters, which can be measured only if the secondary donor star is optically identified. In the absence of direct mass-function measurements from phase-resolved optical spectroscopy, we still have to rely on X-ray spectral and timing modeling and other indirect clues. To bring this point sharply into focus note that in case of the first ultraluminous pulsar, only the X-ray mass function is measured (Bachetti et al. 2014), when the optical secondary is unknown and most of the orbital parameters are yet to be measured. However, exploring the key physical characteristics of a SIMBH model, let us consider the space-fixed Cartesian coordinate system labeled $(z,x,y)$, with $z$ as a plane-of-sight, and the axis $s$ of the M82X-2-fixed frame as the rotation axis. A schematic plot is given in Fig. 3. Here and throughout we now use following notational conventions. The angles $\theta$ and $\phi$ are spherical polar coordinates. The observed pulses are produced because of periodic variations with time of the projection on the plane-of-sight, $d_{zx}(t)$, of the vector $\vec{d}(t)$ collinear to $\vec{n}(t)$ ($\vec{d}(t) = d \frac{\vec{n}(t)}{|\vec{n}(t)|}$), where $\vec{n}(t)$ is the normal to the plane of the proto-matter disk at the moment $t$. The $\vec{n}(0)$ lies in the plane of $zs$. So, these pulsations are due to the fact that the visible surface is less at one moment than at another. The Fig. 4 explains the spherical triangle. That is, given a unit sphere, a spherical triangle on the surface of the sphere is defined by the great circles connecting three points $u, v,$ and $w$ on the sphere (shown at top). The lengths of these three sides are $\alpha = (s, n)$ (from $u$ to $v$), the
Fig. 3.— A schematic plot explaining the spherical triangle solved by the law of cosines. The space-fixed Cartesian coordinate system is labeled (z, x, y), with zx as a plane-of-sight. Axis s of the M82X-2-fixed frame is rotation axis. The angles θ and φ are spherical polar coordinates. The line of nodes N is defined as the intersection of the equatorial and proto-matter disk planes. It is perpendicular to both the z axis and vector \( \vec{n}(t) \), where \( \vec{n}(t) \) is the normal to the plane of proto-matter disk at moment \( t \). The \( \vec{n}(0) \) lies in the plane of zs. The lengths of three sides of a spherical triangle (shown at top) are \( \theta = \hat{(z, s)} \), \( \alpha = \hat{(s, n)} \) and \( \beta = \hat{(z, n)} \). The vertex angle of opposite \( \beta \) is \( \Omega t \).

The axial tilt \( \theta = \hat{(z, s)} \) (from u to w), and \( \beta = \hat{(z, n)} \) (from v to w). The angles of the corners u and e opposite \( \beta \) equal \( u = e = \Omega t \). The proto-matter disk was shifted from the orbital direction on angle \( \delta = \theta - \alpha \) towards the equator. The projection \( d_{zx}(t) \) is then written

\[
d_{zx}(d, \theta, \phi, \alpha, t) = \sqrt{d_z^2(d, \theta, \alpha, t) + d_x^2(d, \theta, \alpha, \phi, t),}
\]

where

\[
d_z(d, \theta, \alpha, t) \equiv \vec{d}(..., t) \cdot \vec{e}_z = d \cos \beta(\theta, \alpha, t),
\]

and

\[
d_x(d, \theta, \alpha, \phi, t) \equiv \vec{d}(..., t) \cdot \vec{e}_x = \frac{d \sin \beta(\theta, \alpha, t) \cos \phi_n(\theta, \alpha, \phi, t).}{16}
\]

Here the \( \vec{e}_z \) and \( \vec{e}_x \) denote unit vectors along the axes z and x, respectively, \( \phi_n = \phi + A \) is the azimuthal angle of vector \( \vec{n}(t) \). The vertex angle opposite the side \( \alpha \) is \( A \). To the extent that all of the rotational energy of M82X-2 is dissipated as thermal defuse X-ray blackbody radiation, this may escape from the event horizon to outside world only through a thin belt area \( S \). The radiation arisen from per area of surface is \( \sigma T_s^4 \), where \( T_s \) is the surface temperature, \( \sigma \) is the Stefan-Boltzmann constant. Therefore, the pulsed luminosity \( \tilde{L} \) will be observed if and only if the projection of the belt area \( S_{zx} = 2\pi R_g d_{zx}(d, \theta, \phi, \alpha, t) \) on the plane-of-sight zx is not zero. So, pulsed luminosity reads

\[
\tilde{L}(R_g, d, T_s, \theta, \phi, \alpha, t) = S_{zx} \sigma T_s^4 = \frac{2\pi R_g d_{zx}(d, \theta, \phi, \alpha, t) \sigma T_s^4}{L_0(M, d, T_s) \Phi(\theta, \phi, \alpha, t)},
\]

where the amplitude and phase, respectively, are

\[
L_0(M, d, T_s) \approx 1.05 \times 10^4 \text{ erg s}^{-1} \text{ M} \text{ d T}_s^4 \text{ m K}^{-4},
\]

\[
\Phi(\theta, \phi, \alpha, t) \equiv \sqrt{1 - \sin^2 \beta \sin^2(\phi + A)}.
\]

The spherical triangle is solved by the law of cosines

\[
\cos(\beta(\theta, \alpha, t)) = \cos \theta \cos \alpha + \sin \theta \sin \alpha \cos \Omega t,
\]

\[
\cos(A(\theta, \alpha, t)) = \frac{\cos \alpha - \cos \theta \cos \beta}{\sin \theta \sin \beta}.
\]
Consequently, the pulsed flux can be written in the form
\[ \tilde{F}(R_g, d, \theta, \phi, \alpha, t) = F_0(M, d) \Phi(\theta, \phi, \alpha, t). \]  
(20)
where, given the distance \( D \approx 3.6 \text{ Mpc} \) to the galaxy M82 \cite{Bachetti2014}, the flux amplitude is
\[ F_0(M, d) = \frac{L_0(M, d)}{4\pi D^2} \approx 6.8 \times 10^{-48} \text{erg s}^{-1} \text{cm}^{-2} \]
\[ \times \frac{M}{M_\odot} \frac{d}{m} \frac{T_4^4}{K^4}. \]  
(21)
Thus, the theoretical model of periodic source M82X-2 left six free parameters: \((M, d, T_4, \theta, \phi, \alpha)\). The figure Fig. 4 reveals the diversity of the behavior of characteristic phase \( \Phi(\theta, \phi, \alpha, x = \Omega t) \) profiles versus the time, viewed at given position angles \((\theta, \phi, \alpha)\). The observed X-ray pulse is further determined by the complicated transfer of X-ray photons from the surface of M82X-2 through regions of external accreting plasma. At hand look, the position angles being the parameters of a model function can be evaluated via nonlinear regression analysis to the approximate solution of overdetermined systems to best fit a data set from observed pulsed profile of M82X-2. These missing ingredients are the shortcomings of present framework, which will be solved by iterative refinement elsewhere. Now according to \( M \), for maximum value of pulsed luminosity either at \( \beta = \pi s \) or \( \phi + A = \pi s (s=0,1,2,...) \), we have \( L_0(M, d, T_4) = \bar{L}(3-30 \text{ keV}) = 4.9 \times 10^{39} \text{erg s}^{-1} \) or \( F_0(M, d) = \bar{F}(3-30 \text{ keV}) \approx 3.16 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \). Hence the surface temperature scales \( \propto T_4^{-4} \) with the black hole mass:
\[ \frac{M}{M_\odot} = \frac{4.66 \times 10^{35} K^4}{T_4^4} \frac{m}{d}. \]  
(22)
That is, a cooler radiation surface implies a bigger black hole. If we further assume that the persistent emission \(-\bar{L}(0.3-10 \text{ keV}) = 1.8 \times 10^{40} \text{erg s}^{-1} - \) from M82X-2 is isotropic, we may impose a strict Eddington limit on the mass transfer rate that can be accepted by the black hole, \( \bar{L} < L_{\text{Edd}} \approx 1.3 \times 10^{38} \frac{M_\odot}{M} \text{ erg s}^{-1}. \) This imposes stringent constraint on the lower limit of black hole mass
\[ \frac{M}{M_\odot} > 138.5, \quad R_g > 408.6 \text{ km}, \]  
(23)
because for an accreting of \( \sim 10 \) per cent of the Eddington limit - a fairly typical accretion rate for a high-state black hole - this points towards a rough estimate of upper limit of mass \( M < 1385 M_\odot \).

### 3.4. More accurate determination of upper mass limit of M82X-2

For the knowledge of upper mass limit of M82X-2, a good progress can still be made by establishing a direct physical relation between masses of M82X-2 and M82X-1, and then one should rely on the available mass estimates of the latter (e.g. \cite{Okajima2006}; \cite{Mucciarelli2006}; \cite{Dewangan2006}; \cite{Stobart2006}; \cite{Patruno2006}; \cite{Portegies2007}; \cite{Roberts2007}; \cite{Casella2008}; \cite{Feng2010}; \cite{Feng2011}; \cite{Pasham2014}). The controversy, however, is with their mass range. As one may envisage, a different mass estimates of M82X-1 may yield different mass values of M82X-2. So, we should be careful in choosing the most accurate black hole mass measurement to date. As the centroid of the persistent emission is between M82X-2 and M82X-1, we suppose that accreting onto a black hole is well approximated by the relation \( L_{\text{acc}} = \eta c^2 \dot{M} = \frac{\dot{L}}{L_{\text{Edd}}} \). This gives \( \dot{M}_1/\dot{M} = \frac{T_1}{\bar{T}} \approx 5.556. \) According to MTBH, we have \( \dot{M} \propto M^2 \) for both the collisionless and the hydrodynamic spherical accretions onto black hole \cite{Ter-Kazarian2014, Ter-Kazarian2015a}. Making use of these relations gives
\[ \dot{M}_1 \approx 2.357 M. \]  
(24)

The M82X-1 is a good candidate for hard state ULXs which may be one of the very few ULXs that change their spectral state during outbursts, switching from a hard to a thermal state \cite{Feng2011}. The type-C low frequency quasi-periodic oscillations and broadband timing noise, detected in the two XMM-Newton observations in 2001 and 2004, in the central region of M82 \cite{Strohmayer2003}; \cite{Dewangan2006}; \cite{Mucciarelli2006} and later confirmed to originate from the M82X-1 \cite{Feng2007}, suggest that the ULX harbors a massive black hole. The mass estimate by \cite{Dewangan2006} is based on the
assumption that M82X-1 also follows well established relation of the photon spectral index versus QPO frequency, $\Gamma - \nu_{QPO}$, found for the Galactic X-ray binaries in their high or intermediate states. The resulting IMBH mass for M82X-1 is in the range of $25 - 520 M_\odot$. However, there may be systematic errors in the photon indices measured with XMM-Newton and Rossi X-ray Timing Explorer (RXTE) due to contamination from nearby sources, as indicated by large apparent changes in the effective absorption column. Another mass estimate by (Casella et al. 2008) is inferred from the correlations with the X-ray luminosity and type C QPO frequency. This method is based on the correlation between characteristic frequencies, on the fundamental plane and on the variability plane of accreting black holes. Exploring this method, the black hole masses inferred from the characteristic frequencies are all about $10^3 - 10^4 M_\odot$ indicating that ULXs contain IMBHs (Casella et al. 2008; Feng & Soria 2011). But, these results were not without problems, notably pointed out by the same authors. Such mass estimates are based on scaling relations which use low-frequency characteristic timescales which have large intrinsic uncertainties. In particular, it was unclear whether these mHz oscillations are indeed the Type-C analogs of stellar mass black, and both the Type-C and the mHz oscillations are variable, resulting in a large dispersion in the measured mass of $25 - 1300 M_\odot$. Positive identification of the emission states requires both timing and spectral information. Consequently, with simultaneous observations exploiting the high angular resolution of Chandra to isolate the ULX spectrum from diffuse emission and nearby sources and the large collecting area of XMM-Newton observations of M82 to obtain timing information, Feng & Kaaret (2010) found surprisingly that the previously known QPOs in the source disappeared. The light curve was no longer highly variable and the power spectrum was consistent with that of white noise. The energy spectrum also changed dramatically from a straight power-law to a disk-like spectrum. The disappearance of QPOs and the low noise level suggest that the source was not in the hard state. All results are well consistent with that expected for the thermal state.
The monitoring data from RXTE indicate that these Chandra and XMM-Newton observations were made during the source outbursts, suggesting that M82X-1 usually stays in the hard state and could transition to the thermal state during outbursts. The spectral fitting suggests that the ULX contains a close to Eddington ($L_{\text{disk}}/L_{\text{Edd}} \sim 2$) rapidly spinning IMBH of $200 - 800 M_\odot$ masses. The thermal dominant states are all found during outbursts. Nonetheless, modeling of X-ray energy spectra during the thermal-dominant state using a fully relativistic multi-colored disk model has large uncertainties owing to both systematic and measurement errors. In addition to the large mass uncertainty associated with the modeling, the same authors also found that the energy spectra can be equally well-fit with a stellar-mass black hole accreting at a rate of roughly $160 \text{ ergs s}^{-1}$.

The discovery of a stable $3:2$ high-frequency periodicity simultaneously with the low-frequency mHz oscillations allows for the first time to set the overall frequency scale of the X-ray power spectrum. This result not only asserts that the mHz quasi-periodic oscillations of M82X-1 are the Type-C analogs of stellar-mass black holes but also provides an independent and the most accurate black hole mass measurement to-date. Assuming that one can scale the stellar-mass relationship, they estimate the black hole mass of M82X-1 to be $428 \pm 105 M_\odot$. They also estimate the mass using the relativistic precession model, which yields a value of $415 \pm 63 M_\odot$. Combining the average 2-10 keV X-ray luminosity $P_{\text{X-ray}}$ of the source of $5 \times 10^{40} \text{ ergs s}^{-1}$ with the measured mass suggests that the source is accreting close to the Eddington limit with an accretion efficiency of $0.8 \pm 0.2$.

Making use of the mass values $428 \pm 105 M_\odot$ with (24), we provide, therefore, the mass estimate for M82X-2:

$$M \approx 138.5 - 226 M_\odot, \quad R_g \approx 408.6 - 666.7 \text{ km},$$

Rotation speed at surface of M82X-2 with upper limit mass $226 M_\odot$ as rigidly spinning IMBH configuration of angular velocity $\Omega$ equals $v = R_g \Omega \approx 3.06 \times 10^8 \text{ cm s}^{-1}$. We also have slightly improved the lower mass limit $323 M_\odot$ of M82X-1 given by (Pasham et al. 2014) to $326.5 M_\odot$. Combining (25) and (22), we obtain then

$$2.06 \times 10^{33} < \frac{T^2}{K^4} \frac{d}{m} < 3.34 \times 10^{33}. \quad \text{(26)}$$

For reasons that will become clear below, next, in our setting we retain the rather concrete proposal of non-spinning black holes (Ter-Kazarian 2014, 2015b), i.e. the neutrino flux from spinning M82X-2 might as well be highly beamed along the plane of proto-matter disk and collimated in very small opening angle. For the values (25), this yields the constraints

$$7.5 \times 10^{-7} \frac{d}{m} < \theta_v \sim \varepsilon_d < 1.2 \times 10^{-6} \frac{d}{m}. \quad \text{(27)}$$

Besides, the $\varepsilon_d$ is likely to be about an order of
magnitude \( \sim 10^{-5} \) for M82X-2. Therefore,
\[
d \simeq 61 - 100 \text{ m}, \quad \epsilon_d \simeq (4.6 - 7.5) \times 10^{-5},
\]
is a good guess for the thickness of proto-matter disk at the edge of event horizon. This, together with (20), give \( T_s \simeq 7.6 \times 10^7 \text{ K} \). Thus, M82X-2 indeed releases \( \sim 99.6\% \) of its radiative energy predominantly in the X-ray bandpass of 0.3 – 30 keV. However, the studies in other wavelengths well give us useful information on its physical nature and environment. From Wien’s displacement law we obtain the wavelength \( \lambda_{\text{max}} \simeq 0.381 \text{ nm} \) at which the radiation curve peaks, which corresponds to energy \( h\nu_{\text{max}} \simeq 3.2 \text{ keV} \). As an immediate corollary to the assumption that the emission arisen from accretion is isotropic, we are able to infer the most important ratios of the pulsating and persistent luminosities to the isotropic Eddington limit for M82X-2:
\[
\frac{\langle L \rangle}{L_{\text{Edd}}} \simeq 0.17 - 0.28, \quad \frac{T}{T_{\text{Edd}}} \simeq 0.63 - 1.03,
\]
respectively, where \( L_{\text{Edd}} \simeq (1.75 - 2.85) \times 10^{40} \text{ erg s}^{-1} \). These properties appear consistent with the sub-Eddington hard state, which given the observed luminosities of M82X-2 suggests the presence of SIMBH with a dynamical mass (26). Given the angular velocity \( \Omega = \frac{2\pi}{P} = 1.37 \text{ s} \), we may calculate the rotational kinetic energy \( E_{\text{rot}} = \frac{1}{2} I \Omega^2 \) of M82X-2, where \( I = \frac{2}{5} M R_g^2 \) is the moment of inertia if M82X-2 is regarded as the rigidly spinning canonical configuration of mass \( M \) and radius \( R_g \). Hence
\[
E_{\text{rot}} \simeq (3.72 - 16.17) \times 10^{51} \text{ erg}. \tag{30}
\]
When all energy thermalized, radiation emerges as a blackbody. A significant fraction of the accretion M82X-2 surface radiates the accretion luminosity at temperature
\[
T_b = \left( \frac{L_{\text{acc}}}{4\pi R_g^2} \right)^{1/4} \simeq \left( \frac{L_{\text{Edd}}}{4\pi R_g^2} \right)^{1/4},
\]
such that \( T_b \simeq (3.88 - 5.37) \times 10^6 \text{ K} \). The gravitational energy of each accreted electron-proton pair turned directly into heat at (shock) temperature \( T_{sh} \): \( 3kT_{sh} = G M_{\text{acc}}/R_{\text{ad}} \), so \( T_{sh} \simeq 1.8 \times 10^{12} \text{ K} \). Hence typical photon energies of persistent radiation lies between \( kT_b \simeq 0.34 \text{ keV} \leq h\nu \leq kT_{sh} \simeq 180 \text{ MeV} \). So, M82X-2 is persistent X-ray and possibly gamma-ray emitter. Also, given the mass of the most brightest source M82X-1 of persistent X-ray radiation, typical photon energies of persistent radiation lie in range \( kT_{b(X1)} \simeq 0.3 \text{ keV} \leq h\nu \leq kT_{sh} \simeq 180 \text{ MeV} \).

### 3.5. The mass of companion star and orbit parameters

Once the mass scaling of M82X-2 is accomplished, this can potentially be used further to quantify the association between the M82X-2 and the optical secondary donor star in X-ray binary. The orbital period \( P_o \) is a key parameter for dynamical mass measurement. From Fig. 2 the separation of the two masses is \( a \), and their distances from the center of mass are \( a_1 \) and \( a_2 \). The highly circular orbit, combined with the mass function \( f(M, M_n, i) = 2.1 M_n \), the lack of eclipses and assumption of a Roche-lobe-filling companion constrain the inclination angle to be \( i < 60^\circ \) [Bachetti et al. 2014]. These allow to determine the mass \( M_2 \) of donor star:
\[
\frac{M_2}{M_2} = \left\{ \begin{array}{ll}
48.3, & \text{for } M = 138.5 M_\odot, \\
64.9, & \text{for } M = 226 M_\odot.
\end{array} \tag{32}\right.
\]
Thus, optical companion is a typical O/B supergiant, which evolves away from the main sequence in just a few million years. The binary separation can be computed with Kepler’s Law \( a^3 = G(M_1 + M_2)P_o^2/4\pi^2 \). The Doppler curve of the spectrum of NuSTAR J095551+6940.8 shows a \( P_o = 2.5 \)-day sinusoidal modulation arisen from binary orbit [Bachetti et al. 2014]. All these give the projection of the orbital velocity of M82X-2 along the line of sight \( v_1 = \frac{2\pi}{P_o} a_1 \sin i \approx 200 \text{ km s}^{-1} \), and hence \( a_1 \sin i \approx 9.9 R_\odot \). The absence of eclipses implies \( \cos i > \frac{R}{a} \), where \( R \) is the radius of companion donor star. Hence
\[
R > \left\{ \begin{array}{ll}
22.1 R_\odot, & \text{for } M = 138.5 M_\odot, \\
25.7 R_\odot, & \text{for } M = 226 M_\odot.
\end{array} \tag{33}\right.
\]
As well as \( a_1 > 11.4 R_\odot \), \( a_2 > 32.9 R_\odot \) for \( M/M_\odot = 138.5 \); and \( a_1 \) is the same, \( a_2 > 39.9 R_\odot \) for \( M/M_\odot = 226 \). The Roche lobe radius \( R_L \) for donor star is
\[
R_L > \left\{ \begin{array}{ll}
15 R_\odot, & \text{for } M = 138.5 M_\odot, \\
14.3 R_\odot, & \text{for } M = 226 M_\odot.
\end{array} \tag{34}\right.
\]
Thus, the M82X-2 and donor star constitute the semi-detached binary, accreting through Roche-lobe overflow. Donor star exceeds its Roche lobe \((R > R_L)\), therefore its shape is distorted because of mass transfer from donor star through the inner Lagrange point \(L_1\) to the M82X-2. The accretion stream is expected to be rather narrow as it flows through the \(L_1\) point and into the Roche lobe of the primary.

### 3.6. Spin-up rate and the torque added to M82X-2

All accreting pulsars show stochastic variations in their spin frequencies and luminosity, including those displaying secular spin-up or spin-down on long time scales, blurring the conventional distinction between disk-fed and wind-fed binaries (Bildsten et al. 1997). Pulsed flux and accretion torque are strongly correlated in outbursts, even anticorrelated, in persistent sources. The observed secular spin-up rate can be accounted for quantitatively if one assumes the reduction of the torque on the rapidly spinning object. Continuing on our quest, below we determine the conditions under which pulsed source M82X-2 spins up and hence gains rotational energy as matter is accreted, i.e. we discuss the relationship between the properties of the exterior flow and the measured rate of change of angular velocity \(d\Omega/dt\). Although measurements of spin-up or spin-down appear to be the most promising method for determining the angular momentum transport by the inflowing matter, which in turn, may provide information about pattern of material flow outside the event horizon of SIMBH, the extraction of this information from such measurements clearly requires some care. We explore the relationship between the torque \((= l)\) flux through the event horizon, spin-up rate of SIMBH and the rate of change of its rotational energy. The rates of change of the SIMBH angular velocity and of the rotational energy can be related to the flux of torque across the event horizon boundary as follows. The rate of change of the torque is given by (Ghosh et al. 1977)

\[
\frac{d}{dt}(l\Omega) = \dot{M}l,
\]

where \(I\) is the moment of inertia, and \(l\) is the torque added to the SIMBH per unit mass of accreted matter. Equation (35) gives for the rate of change of angular velocity

\[
\frac{d\Omega}{dt} = \frac{\dot{M}}{l_{bh}} \left[ l\Omega - \Omega^2 R_{gir}^2 \left( \frac{M}{l} \frac{dI}{dM} \right) \right],
\]

where \(l_{bh} \equiv l\Omega\), and \(R_{gir}\) is the radius of gyration of SIMBH. The rate of change of the rotational energy is

\[
\frac{dE_{rot}}{dt} = \frac{d}{dt} \left( \frac{1}{2} I\Omega^2 \right).
\]

To make further progress we recast (36) and (37) into the form

\[
\frac{dE_{rot}}{dt} = \dot{M} \left[ l\Omega - \frac{1}{2} \Omega R_{gir}^2 \left( \frac{M}{l} \frac{dI}{dM} \right) \right].
\]

When \(\frac{M}{l} \frac{dI}{dM} > 0\), which is generally the case, the SIMBH’s behavior can be conveniently characterized by the dimensionless parameter

\[
\zeta \equiv \frac{l}{2 \Omega R_{gir}^2} \left( \frac{M}{l} \frac{dI}{dM} \right)^{-1}.
\]

Thus the black hole loses rotational energy and spins down for \(\zeta < 1/2\), whereas it gains rotational energy and spins up for \(\zeta > 1\); for \(1/2 < \zeta < 1\) the black hole spins down even though it is gaining rotational energy. The logarithmic derivative \(\frac{df}{dl}\) for canonical configuration, i.e. spinning uniform-density sphere with mass \(M\) and radius \(R_g\), is \(\frac{df_{lin}}{dl_{lin}} = \frac{d}{dl_{lin}} \log (\frac{2}{3} M R_g^2) = 3\), so

\[
\zeta = \frac{l}{3\Omega R_{gir}^2}.
\]

where \(R_{gir}^2 = I/M = 2g R_g^2\). For the spin up regime of M82X-2 when \(\zeta \approx 0.073 \frac{l}{3\Omega R_{gir}^2} > 1\), we obtain \(l > 2.192 R_g^2 \text{s}^{-1}\), so

\[
\frac{d}{dt} \log (\frac{2}{3} \Omega R_{gir}^2) > \frac{1}{3}\frac{d}{dt} \log (\frac{\dot{M}}{P} M)
\]

The time derivative of the angular velocity (36) gives

\[
l = \frac{4\pi R_g^2}{5P} \left( 3 - \frac{\dot{P}}{P} \frac{M}{\dot{M}} \right).
\]

Combining \(\dot{M} \simeq 6.35 \times 10^{-7} M_\odot \text{yr}^{-1}\), and a linear spin-up \(\dot{\nu}\) of the NuSTAR J095551+6940.8 pulsar,
from \( l \) we obtain the torques added to M82X-2 per unit mass of accreted matter, which satisfy the spin-up condition \( \zeta > 1 \) of \( \zeta > 1 \):

\[
l \approx \begin{cases} 
1.1 \times 10^{11} \text{km}^2\text{s}^{-1}, & \text{for } M = 138.5 \, M_\odot, \\
9.8 \times 10^{11} \text{km}^2\text{s}^{-1}, & \text{for } M = 226 \, M_\odot.
\end{cases}
\]

(43)

This is not a final report on a closed subject, and needless to say once again that astronomers are not yet at the end of producing a coherent picture of the ULX Universe, so there is plenty to argue about. We believe that there is still very much to be gained by further study of the issues that we raised in this paper. There are deep conceptual and technical problems involved, and these provide scope for the arguments discussed, which are carefully presented in mathematical and physical terms. It should be emphasized that the key to our construction procedure of both MTBH in general, and suggested model of mighty ultraluminous X-ray pulsations from periodic source M82X-2 in particular, is widely based on the premises of our experience of accretion physics. Therefore, what we have presented here has all the vices and virtues of the classical scenario of runaway core collapse which has always been a matter of uncertainties and controversies. On the other sight, astronomers doubted the existence of the superdense proto-matter sources, away from the accretion physics. Models of this type have a long tradition of precursors that dates back to the pioneering seminal papers by \textbf{Ambartsumian (1958, 1961, 1963)}. Since then the very possibility of existence of such sources was rejected, and the idea of the superdense proto-matter was dismissed as a fancy of eccentric astronomer. However, we caution that our entire constructions will be valid as well in the case if some hitherto unknown yet mechanism in Nature will in somehow or other way produce the superdense proto-matter, away from the accretion physics.

4. Concluding remarks

Our analysis of periodic source M82X-2 goes quite on the contrary to the conventional wisdom. The pulsed luminosity of M82X-2 is the most extreme violation of the Eddington limit and could be reconciled with that in the model of common pulsar only by very arbitrary assumptions on geometric beaming of accretion flow on neutron star. Instead of making such assumptions, our approach finds it preferable to return in part to the ideas of MTBH framework to circumvent the alluded obstacles without the need for significant breaking of Eddington limit. The new conceptual element of the implications of MTBH in tackling this problem is noteworthy. This explores the most important processes of spontaneous breaking of gravitation gauge symmetry and rearrangement of vacuum state at huge energies, making room for growth and merging behavior of black holes. Putting apart the discussion of inherent problems of the mass scaling of the black holes in ULXs, we have focused on black hole. We assume the M82X-2 is being SIMBH, resided in the final stage of growth. If this were the case, eventually, a thin co-spinning proto-matter disk driven by accretion would be formed around the spinning proto-matter core. It was tilted from the plane of accretion on a definite angle \( \delta \) towards the equator and has reached out the edge of the event horizon, where a metric singularity inevitably disappears. The energy is carried away then from event horizon through a thin belt area to outside world by both the ultra-high energy neutrinos produced in the superdense proto-matter medium, and the thermal defuse blackbody radiation released from the outer surface layers of ordinary matter of spinning SPC and co-spinning proto-matter disk. All of the rotational energy of SIMBH is dissipated as thermal defuse blackbody X-ray radiation to outside world. As M82X-2 spins, we see pulses because of the axial tilt or obliquity. That is, the M82X-2 is the emitter of both persistent and pulsating X-rays. We derive the general profiles of pulsed luminosity and X-ray flux of M82X-2. Hence M82X-2 indeed releases \( \sim 99.6\% \) of its radiative energy predominantly in the X-ray bandpass of 0.3 – 30 keV. The resulting theoretical model necessarily includes a number of poorly known parameters. We give a quantitative account of all the energetics, a dynamical mass scaling and orbital parameters of the semi-detached X-ray binary containing primary M82X-2 and the secondary massive O/B-type donor star, accreting through Roche lobe overflow. The position angles can be evaluated from rigorous comparison with the behavior of observed pulsed light curve of M82X-2, which will be discussed in a future publication.
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