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ON OBSERVATIONAL PHENOMENA RELATED TO KERR SUPERSPINARS

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Abstract. We investigate possible signatures of a Kerr naked singularity (superspinar) in various observational phenomena. It has been shown that Kerr naked singularities (superspinars) have to be efficiently converted to a black hole due to accretion from Keplerian discs. In the final stages of the conversion process the near-extreme Kerr naked singularities (superspinars) provide a variety of extraordinary physical phenomena. Such superspinning Kerr geometries can serve as an efficient accelerator for extremely high-energy collisions, enabling a direct and clear demonstration of the outcomes of the collision processes. We shall discuss the efficiency and the visibility of the ultra-high-energy collisions in the deepest parts of the gravitational well of superspinning near-extreme Kerr geometries for the whole variety of particles freely falling from infinity. We demonstrate that ultra-high-energy processes can be obtained with no fine tuning of the motion constants and the products of the collision can escape to infinity with efficiency substantially higher than in the case of near-extreme black holes. Such phenomena influence the radiative processes taking place in the accretion disc, and together with the particular generated geometry they influence the observed radiation field. Here we assume the "geometrical" influence of a Kerr naked singularity on the spectral line profiles of radiation emitted by monochromatically and isotropically radiating point sources forming a Keplerian ring or disc around such a compact object. We have found that the profiled spectral line of the radiating Keplerian ring can be split into two parts because there is no event horizon in the naked singularity spacetimes. The profiled lines generated by Keplerian discs are qualitatively different for a Kerr naked singularity and black hole spacetimes broadened near the inner edge of a Keplerian disc.

Keywords: Kerr superspinar, particle collisions, spectral line profiles.

1. Introduction

String Theory, one of the most relevant candidates for the theory of all physical interactions and quantum gravity, indicates a possibility to be tested in relativistic astrophysics. Gimon and Hořava [1] have shown that Kerr superspinars with mass M and angular momentum J violating the general relativistic limit on the spin of black holes ($a = J/M^2 > 1$) could be primordial remnants of the high-energy phase of a very early period in the evolution of the Universe, when the effects of String Theory were relevant. It is assumed that the spacetime outside a Kerr superspinar of radius R, where the stringy effects are irrelevant, is described by the standard Kerr geometry. The exact solution describing the interior of the superspinar is not yet known in the 3+1 theory, but it is considered that its extension is limited to $0 < R < M$ covering thus the region of causality violations (naked time machine) and physical singularity and still allowing for the presence of the most interesting astrophysical phenomena related to the Kerr naked singularity spacetimes [1]; we assume here $R = 0$.

The properties of the surface of Kerr superspinars are usually assumed to correspond to those of the black hole horizon, i.e., the surface is assumed to serve as a one-way membrane. Of course, we can introduce assumptions of non-zero reflexity (or emissivity) as discussed in [2]. Here we assume for simplicity surface properties resembling those of the black hole horizon.

2. Ultra-High-Energy Collisions

Ultra-high energy collisions could be relevant in the field of near-extreme superspinning Kerr geometries with spin $a = 1 + \delta\,(\delta \ll 1)$ that can well describe the exterior of primordial Kerr superspinars. They have to be converted into (near-extreme) black holes due to accretion. Such a classical instability works on large time scales so that primordial superspinars can quite well survive to the era of high-redshift quasars (at $z \geq 2$) [3]. Of course, the travel time of the colliding particles to the collision point has to be smaller then the conversion time of the Kerr superspinar [4]. Collisions of particles in the field of the near-extreme superspinars that exhibit extremely large energy in the CM system occur if the collisions take place at the special surface $r = M$, or in its close vicinity. These ultra-high-energy processes occur quite naturally for a wide range of motion constants of the particles freely falling from infinity. Assuming two particles with constants of motion, the covariant energy $E_i = m_i$, the azimuthal angular momentum l_i, and the angular momentum q_i related to the total angular momentum,

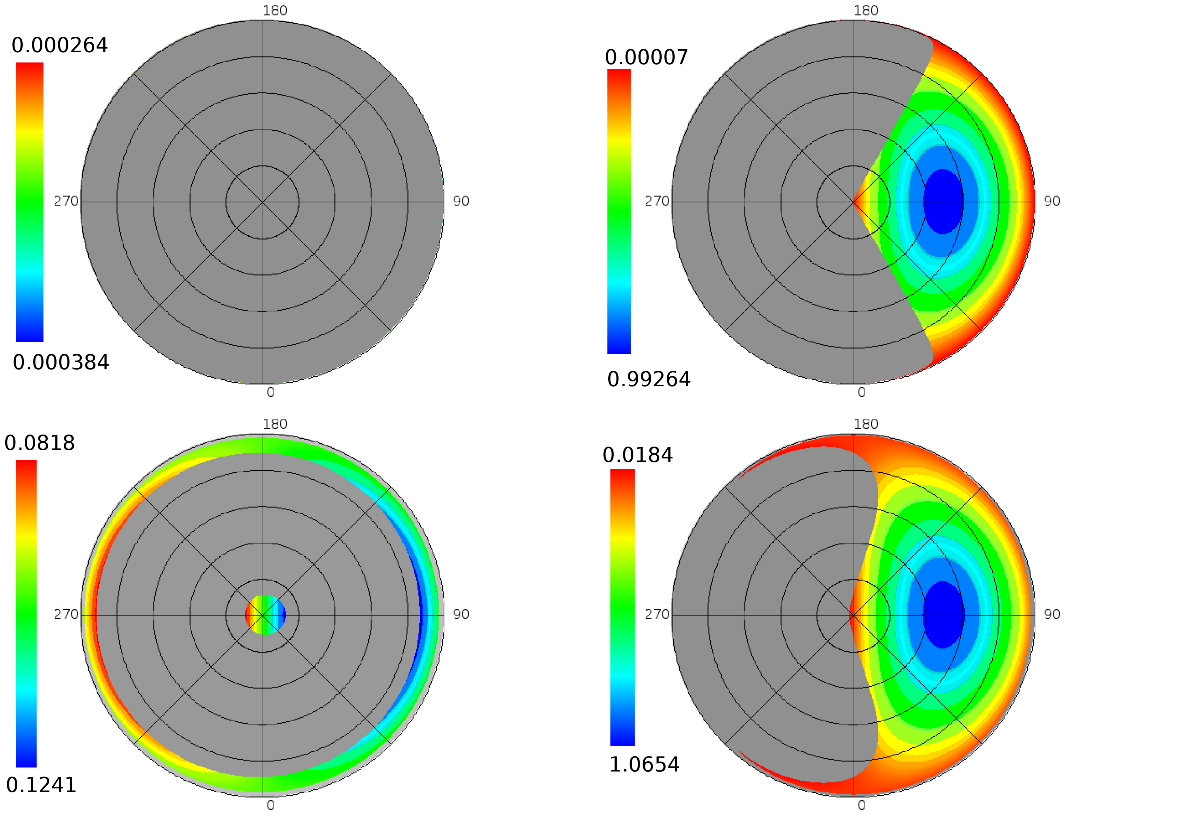

Figure 1. Escape cones of LNRF. The LNRF source at r = M and representative latitude values are $\theta = 5°$ (left) and 85° (right). The superspinar spin is set to a representative value $a = 1 + 10^{-7}$ (upper row) and $a = 1 + 10^{-2}$ (lower row). The frequency shifts of the photons are represented by the colour code with the range given in each case.

where $i = 1, 2$, in zeroth approximation the formula for the energy of the collision in the centre of the mass system reads

$$E^2_{CM} = \frac{2m_1 m_2}{1 + \cos^2\theta} \frac{(2 - l_1)(2 - l_2)}{\delta}. \tag{1}$$

For impact parameters $l_1 = l_2 = -5$ one obtains extremal efficiency. The corresponding energy of collision then reads

$$E^2_{CM} = \frac{2m_1 m_2}{1 + \cos^2\theta} \frac{49}{\delta}. \tag{2}$$

The most efficient energy processes occur for colliding particles with negative axial angular momentum (impact parameter) with maximal magnitude $l \sim 5$, when the local CM energy larger by a factor of $\frac{7}{2}$ than those corresponding to the simplest case of collisions of inward and outward radially moving particles colliding at $r = M$[4].

The possibility of escape of the particles generated by ultra-high-energy collisions can be determined by constructing escape photon cones that well represent the escape of ultra-relativistic particles (we can expect direct formation of ultra-high energy photons). For simplicity, our attention is restricted to the case of collisions of radially moving particles of identical rest energy that have the CM system identical with the LNRF since they move purely radially relative to such frames [4]. The resulting escape cones and the related frequency shift are given in Fig.1. We observe strong restriction of the extension of the escaping photon cone and a strong decrease in the frequency shift of the escaping photons with decreasing Kerr superspinar spin for a small latitude $\theta = 5°$, while for a large latitude $\theta = 85°$ the escaping cone remains large in the part related to photons comoving relative to the spacetime, and the frequency shift of the photons remains very small. In fact, for $\theta = 5°$ the behavior of both the escaping cone and the frequency shift in the field of Kerr superspinars with $a = 1 + 10^{-7}$ strongly resembles their behaviour in the field of near-extreme Kerr black holes — almost precisely radially directed photons can escape with largely decreasing frequency shift. In such situations the ultra-high energy of the photons occurs only in situations when ultra-heavy particles collide and their rest energy corresponds to the energy of photons observed at large distances.

From the behaviour of the frequency shift of the radiated photons it follows that there is a high probability to observe ultra-high energy photons if the collision occurs near the equatorial plane [4].

We conclude that near-extreme superspinning Kerr geometries are much more efficient for the occurrence of ultra-high energy collisions then the vicinity of the

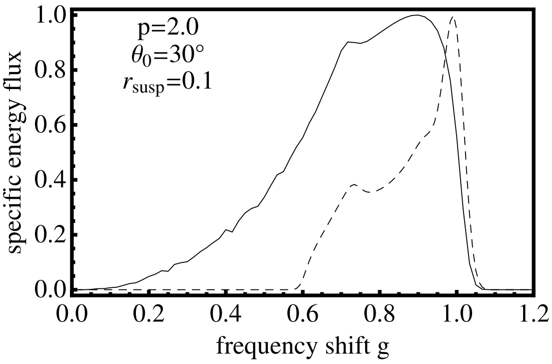

FIGURE 2. Profiled lines from a Keplerian disc plotted for two representative values of spin $a = 0.9999$ (solid) and 3.0 (dashed). The disc ranges from $r_{in} = r_{ISCO}(a)$ to $r_{out} = 10$M. The inclination of the observer is $\theta_0 = 30°$.

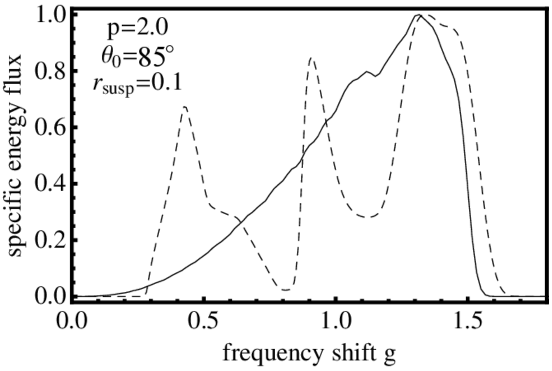

FIGURE 3. Profiled lines from a Keplerian disc plotted for two representative values of spin $a = 0.9999$ (solid) and 3.0 (dashed). The disc ranges from $r_{in} = r_{ISCO}(a)$ to $r_{out} = 10$M. The inclination of the observer is $\theta_0 = 85°$.

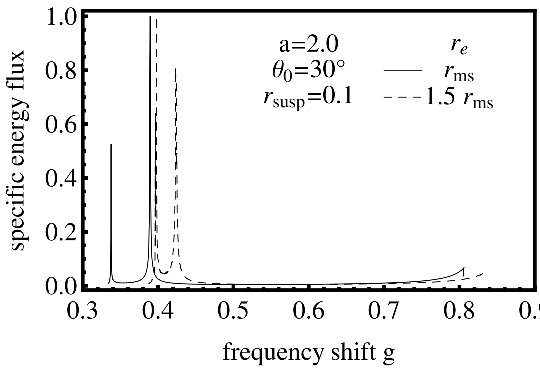

FIGURE 4. Profiled lines from a Keplerian ring plotted for representative value of spin $a = 2.0$ and two Keplerian ring radial size values $r_e = r_{ms}$ (solid) and $r_e = 1.5r_{ms}$ (dashed). The inclination of the observer is $\theta_0 = 30°$.

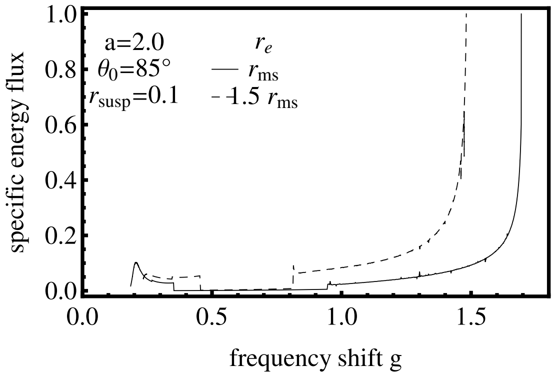

FIGURE 5. Profiled lines from a Keplerian ring plotted for representative value of spin $a = 2.0$ and two values Keplerian ring radial size values $r_e = r_{ms}$ (solid) and $r_e = 1.5r_{ms}$ (dashed). The inclination of the observer is $\theta_0 = 30°$.

black hole horizon, and imply much more efficient escaping of the created photons (ultra-relativistic particles) and an opportunity for distant observers to observe them with such an ultra-high energy.

We plan to study these effects explicitly also in the more complex situations occurring for collisions of "non-radially" moving particles when collisions can be more efficient by a factor of 3.5 than for purely radial collisions.

3. PROFILED SPECTRAL LINE

In our simulations of spectral line profiles we assume that a Keplerian ring (disc) is composed of point sources emitting monochromatic radiation isotropically. Each point emitter moves along a circular geodesic in the equatorial plane. The general formula of the observed flux of the profiled line is given by

$$F_o(\nu_o) = \int I(r) g^4 \delta(\nu_0 - g\nu_e)\,\mathrm{d}\Pi, \tag{3}$$

where $I(r)$ is the emitter radiation intensity, g is the frequency shift of the radiation, $\nu_o(\nu_e = \text{const.})$ is the photon frequency of the observer (emitter) and $\mathrm{d}\Pi$ is the solid angle element intended by the source on the observer sky. The radial dependence of the radiation intensity is assumed in the standard form

$$I(r) \sim 1/r^p. \tag{4}$$

The frequency shift g takes the usual form

$$g = \frac{\sqrt{1 - 2(1 - a\Omega)^2/r_e - (r_e^2 + a^2)\Omega^2}}{1 - \lambda\Omega}, \tag{5}$$

where $\Omega = 1/(a + \sqrt{r_e^3})$ is the angular frequency of the emitter. We illustrate our results in Figs 2–7 where the profiled lines generated in the field of the Kerr superspinars and black holes are compared for a small and large inclination angle of distant observers. When the event horizon is not present, there is an additional group of photons that can reach a distant observer and contribute to the observed profiled lines. They are initially directed inward with the impact parameter below the corresponding value of the photon spherical orbit [5]. Additionally, there is a clear strong functional dependence of the width of the spectral profiled line on the spin parameter a of the Kerr superspinars.

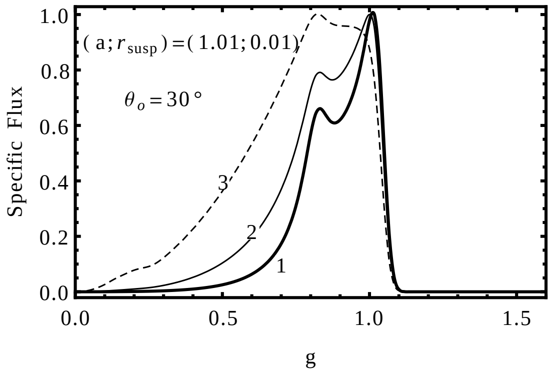

Figure 6. Profiled lines from a Keplerian disk plotted for a representative spin value $a = 1.01$ and three emissivity index values $p = 1$ (thick solid), 2 (solid) and 3 (dashed). The inclination of the observer is $\theta_0 = 30°$.

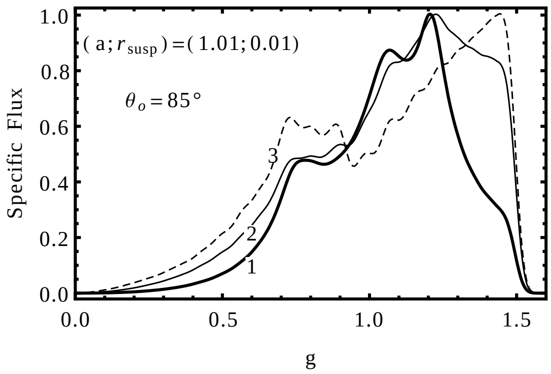

Figure 7. Profiled lines from a Keplerian disk plotted for a representative spin value $a = 1.01$ and three emissivity index values $p = 1$ (thick solid), 2 (solid) and 3 (dashed). The inclination of the observer is $\theta_0 = 85°$.

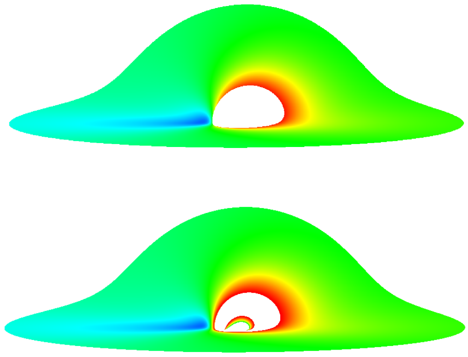

Figure 8. Shapes of Keplerian discs plotted for spin parameters $a = 0.998$(top) and 1.0001(bottom). The disc ranges from $r_{in} = r_{ISCO}(a)$ to $r_{out} = 20$M. The inclination of the observer is $\theta_0 = 85°$.

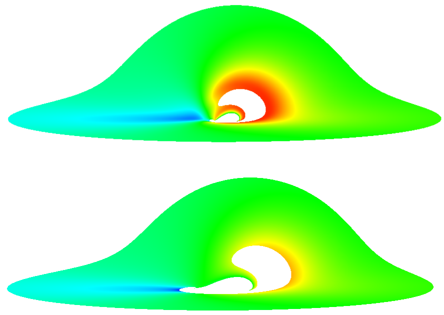

Figure 9. Shapes of Keplerian discs plotted for spin parameters $a = 1.1$ (top) and 3.0 (bottom). The disc ranges from $r_{in} = r_{ISCO}(a)$ to $r_{out} = 20$M. The inclination of the observer is $\theta_0 = 85°$.

In the case of a Keplerian disc, the superspinar "fingerprints" are in the shape of the profiled line and in its frequency range [5]. In the case of a Keplerian ring, the profiled lines "split" into two parts, where the "blue" line is strongly influenced by the superspinar surface radius. Of course, the inclination of the observer plays an important role too, and should be known prior to the analysis. There is strong qualitative difference between the profiled lines created in the field of Kerr superspinars and Kerr black holes. These phenomena related to the profiled lines can be observed even for extremely distant objects. For more details see [5–7]. We expect that the spectral line profiles could be well distinguished by future X-ray satellites, e.g. LOFT [8]

4. Observed shape of the thin Keplerian disc

The radiation also recovers the imprints of Kerr naked singularity spacetime in the shape of thin Keplerian discs. For spins $a > 1$ the additional image is present in the inner part of the disk image. Increasing the spin parameter a, one can clearly see that an additional image creates, in the inner part of the disk image, a complex structure which clearly distinguishes naked singularity spacetimes from black hole spacetimes, as demonstrated in Figs 3, 6 and 7. Of course, phenomena related to the details of innermost parts of Keplerian discs can be observed only in objects that are sufficiently close to the observer, e.g. the supermassive object in the centre of the Galaxy. For detailed information, see [5].

Acknowledgements

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