

## **Astrophysical Applications of the Gravitational Searchlight**

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### *Abstract*

The astrophysical consequences of the blue-shifted radiation emitted in the forward direction by a source moving in an equatorial orbit with radius slightly in excess of 1.5 times the Schwarzschild radius of a highly collapsed central object are examined with special reference to quasistellar objects.

### §(1): *Introduction*

The physical description of matter around collapsed objects has received considerable attention recently since it was realized that accretion onto neutron stars or black holes can be one of the most efficient means of generating radiation. The gravitational energy of the in-falling gas can, in fact, be converted into radiation with mass-energy conversion efficiency of some  $0.06 c^2$  to  $0.42 c^2$ . Recently several binary x-ray sources have been discovered in which mass transfer takes place from a visible primary to a compact secondary which could be a neutron star or a black hole (Pringle and Rees [1] and Shakura and Sunyaev [2]). Typical observed binary systems that emit x rays, e.g., Cyg X - 1, Cen X - 3 seem to suggest a model (Novikov and Thorne [3]) in which the accreting matter, because of its substantial angular momentum, goes into Keplerian orbit around the central object forming a thin disk. The viscous friction tends to brake the inner regions, in the process transporting angular momentum outwards. The loss of angular momentum of the inner regions of the disk causes the gas near the object to spiral inwards, and the gravitational energy released gets converted into radiation.

The radiation field arising from matter moving in the neighborhood of a collapsed object has several interesting features. It has been shown by Chitre et al. [4] (hereafter referred to as Paper I) that a variety of consequences follow if a source of radiation moves in a circular orbit with a radius slightly in excess of  $3 GM/c^2$  in an equatorial plane around a highly collapsed object.

It should be emphasized that even though the last stable circular orbit for a radiating particle is situated at a radial distance of  $6 GM/c^2$ , the winding paths between  $3 GM/c^2$  and  $6 GM/c^2$  are highly relativistic but transient orbits of the particle. These are basically unstable orbits, and the particle makes several rounds of the central collapsed object close to  $3 GM/c^2$  before falling into it (Misner et al. [5]), provided it has high enough velocity to surmount the potential barrier.

A photon emitted in the forward direction from a particle in such an unstable orbit gets strongly blue-shifted when it is received by a distant observer (cf. Paper I). The processes like synchrotron radiation from an electric charge moving around a collapsed object or gravitational radiation emitted by a particle circulating in an orbit of radius slightly in excess of 1.5 times the Schwarzschild radius of a highly collapsed central mass turn out to be too weak to be astrophysically significant [5]. However, the effect investigated in Paper I shows that the forward radiation is blueshifted by the Doppler effect to such an extent that it can overcome the strong gravitational red shift of the central object.

The searchlight effect arises most naturally when the radiating source moves in an equatorial plane of the collapsed object and as a result the radiation is beamed largely in the direction of an observer lying in the equatorial plane of the circulating matter.

It is remarkable that the radiation from a ring-shaped emitting region composed of orbiting particles emitting in a narrow frequency range gets spread over a wide frequency band with the distant observer seeing a  $d\nu/\nu$ -type of spectrum. As discussed in Paper I, this follows from purely geometrical considerations. We wish to discuss the astrophysical consequences of this effect, especially the implications of such an emission spectrum for the observations of quasistellar objects.

### §(2): *Physics of Accretion Disks around Collapsed Objects*

We shall consider the processes that occur near a highly collapsed object of mass  $M$ . Specifically, we wish to consider the quasar phenomenon for which Hoyle and Fowler [6] suggested the gravitational collapse of a supermassive star as a possible mechanism to account for the energetic requirement of strong radio sources. Assuming that a massive object with  $M \gtrsim 10^9 M_\odot$  gets formed out of the interstellar material, the evolutionary processes will eventually cause a contraction of the object towards the Schwarzschild radius. Thus it would appear that a supermassive star would ultimately collapse to become a black hole, and the

likely sites for supermassive black holes are the nuclear regions of galaxies. Let  $M$  be the mass of the black hole. Then the rate of accretion is given by (Novikov and Thorne [3])

$$\dot{M} \approx 10^{11} (M/M_{\odot})^2 (\rho_0/10^{-24} \text{ gm cm}^{-3}) (T_0/10^4 \text{ }^{\circ}\text{K})^{-3/2} \text{ gm sec}^{-1} \quad (2.1)$$

where  $\rho_0$  and  $T_0$ , respectively, refer to the density and temperature of the gaseous material which is being accreted onto the black hole. Inserting typical values,

$$\rho_0 \approx 10^{-27} \text{ gm cm}^{-3} \quad T_0 \approx 10^4 \text{ }^{\circ}\text{K}$$

The mass accretion rate comes out to be

$$\dot{M} \approx 10^8 (M/M_{\odot})^2 \text{ gm sec}^{-1} \quad (2.2)$$

The thickness of the accretion disk  $H$  formed around the black hole will be dictated by the equation of vertical pressure balance and may be expressed in terms of the radial extent of the disc  $D$  as  $H = \alpha D$  where  $\alpha \ll 1$ .

The radial velocity of inflow will evidently depend on the detailed viscous dissipation mechanism which removes the angular momentum outwards and is related to the Keplerian velocity  $V_K$  through the relation (cf. Pringle and Rees [1])

$$V_R \approx 10^{-2} V_K = 10^{-2} \sqrt{GM/r} \approx 10^8 \sqrt{(M/10^9 M_{\odot}) (10^{15} \text{ cm}/r)} \text{ cm sec}^{-1} \quad (2.3)$$

The velocity of inflow and the mass accretion rate suffice to yield the electron density  $n_e$  in the disk (Norman and ter Haar [7]):

$$\begin{aligned} n_e &\approx \frac{\dot{M}}{2\pi r H m_H V_R} \\ &\approx 10^{11} \alpha^{-1} \left( \frac{\dot{M}}{10^8 (M/M_{\odot})^2 \text{ gm sec}^{-1}} \right) \left( \frac{M}{10^9 M_{\odot}} \right)^{-1/2} \left( \frac{r}{10^{15} \text{ cm}} \right)^{-3/2} \text{ cm}^{-3} \end{aligned} \quad (2.4)$$

The accreting gas is expected to contain a magnetic field, and the field strength  $B$  expected in the disk may be estimated by adopting Lynden-bell's arguments [8] based on the shearing of the lines of force to give

$$\frac{B^2}{8\pi} \approx m_H n_e \frac{GM}{4r^3} H^2$$

i.e.,

$$B \approx 10 \alpha^{1/2} (\dot{M}/10^8 (M/M_{\odot})^2 \text{ gm sec}^{-1})^{1/2} (M/10^9 M_{\odot})^{1/4} (r/10^{15} \text{ cm})^{-5/4} \text{ gauss} \quad (2.5)$$

The thickness of the disk can only be roughly estimated from the balance of the vertical forces, and near  $r = 1.5 r_0$  it is approximately given by

$$\alpha = \frac{H}{1.5 r_0} \simeq \frac{\text{speed of sound}}{c} \simeq 10^{-4} \quad \text{for } T \simeq 10^4 \text{ }^\circ\text{K} \quad (2.6)$$

The physical description of the disk around a black hole is thus completely specified in terms of the mass accretion rate and the ambient conditions.

### §(3): *Radiation from Regions Close to the Unstable Orbit*

We shall consider emission from the matter moving in a zone with  $r \gtrsim 1.5 r_0$  around a massive black hole. The accreted matter, as a result of its angular momentum, will make several revolutions around the black hole before either getting sucked into it or escaping out of the gravitational field of the central black hole. In view of the interesting effects arising from sources of radiation moving in relativistic circular orbits with radii slightly in excess of  $1.5 r_0$ , we shall study the effects of radiation from the thermal bremsstrahlung and synchrotron mechanisms resulting from regions close to  $1.5 r_0$ .

We shall examine the two processes separately. Consider the thermal emission from the gas at temperature  $\simeq 10^4 \text{ }^\circ\text{K}$  situated near  $r \gtrsim 1.5 r_0$ . The emission will be in a narrow region around the equatorial plane of the disk, where the flux in the range  $\nu, \nu + d\nu$  is given by [using equation (31) of Paper I]

$$S(\nu) = A(\nu_0)/\nu$$

where

$$\nu_0 \simeq 10^{14} \text{ cps}$$

and

$$\begin{aligned} A(\nu_0) &= 4\sqrt{3} \frac{G^2 H M^2}{c^4} E(\nu_0) \\ &\simeq 2 \times 10^{17} \alpha (M/M_\odot)^3 E(\nu_0) \end{aligned}$$

With the thermal emission from a plasma at temperature  $10^4 \text{ }^\circ\text{K}$  the emissivity is approximately given by (Silk [9])

$$E(\nu_0) \simeq 4.4 \times 10^{-24} n_e^2 \text{ erg cm}^{-3} \text{ sec}^{-1} \quad (3.1)$$

and hence

$$A(\nu_0) \simeq 8.8 \times 10^{-7} \alpha n_e^2 (M/M_\odot)^3 \quad (3.2)$$

From observations for the quasar 3C-273 (Burbidge and Burbidge [10]) we have for emission peaked around the frequency  $\nu_0 \simeq 10^{14} \text{ cps}$  the flux  $\simeq 10^{-24}$ ,

yielding

$$(M/M_\odot)^3 n_e^2 \simeq 10^{46} \alpha^{-1} R_{\text{Mpc}}^2 \quad (3.3)$$

where the distance to the source  $R_{\text{Mpc}}$  is expressed in megaparsecs.

For  $M \simeq 10^{10} M_\odot$  we get  $n_e \simeq 10^8 \alpha^{-1/2} R_{\text{Mpc}} \text{ cm}^{-3}$  and for  $M \simeq 10^8 M_\odot$  we get  $n_e \simeq 10^{11} \alpha^{-1/2} R_{\text{Mpc}} \text{ cm}^{-3}$ . The density of matter from equation (2.4) in the regions near  $r = 1.5r_0$  is approximately  $\gtrsim 10^{10} \alpha^{-1}$  for  $M \simeq 10^{10} M_\odot$  and it is not unreasonable to expect  $n_e$  about a fraction of a per cent in the region  $1.5r_0 \leq r \leq 3r_0$ , and the observed emission could correctly result from a purely thermal process.

The accreted gas will contain a magnetic field which will be sheared and tangled by motions in the gas. Suppose that the turbulent magnetic field has a component  $B_\perp$  perpendicular to the disk. Then synchrotron process would become effective in contributing to the emission of radiation in the forward direction. Inserting the expression for the synchrotron power radiated per electron  $\sim 10^{-21} \gamma'^2 B_\perp^2 \text{ MeV/sec}$  in the usual notation, we get

$$(M/M_\odot)^3 \gamma'^2 B_\perp^2 n_e \simeq 10^{50} R_{\text{Mpc}}^2 \quad (3.3)$$

For  $M \simeq 10^{10} M_\odot$ , we have  $\gamma'^2 B_\perp^2 n_e \simeq 10^{20} R_{\text{Mpc}}^2$  and for  $M \simeq 10^8 M_\odot$ ,  $\gamma'^2 B_\perp^2 n_e \simeq 10^{26} R_{\text{Mpc}}^2$ . Equation (2.5) yields an approximate value of the magnetic field around

$$B_\perp \gtrsim 10 \alpha^{1/2}$$

We then require

$$\gamma'^2 n_e \simeq \begin{cases} 10^{18} \alpha^{-1} R_{\text{Mpc}}^2 & \text{for } M \simeq 10^{10} M_\odot \\ 10^{24} \alpha^{-1} R_{\text{Mpc}}^2 & \text{for } M \simeq 10^8 M_\odot \end{cases}$$

The synchrotron process thus requires a fairly large value of  $\gamma'$  ( $\gtrsim 10^{10}$ ) corresponding to  $n_e \simeq 10^8 \text{ cm}^{-3}$  to account for the observed emission. It is usually believed that the quasar emission is of nonthermal origin due to synchrotron process or due to inverse Compton. We have tried to argue that the emission could possibly have a thermal origin in a narrow frequency range which is then spread over a wide frequency band. The usual objection (Burbidge and Burbidge [10]), that the thermal emission spectrum does not give the observed  $\nu^{-n}$  ( $n \simeq 1$ ) dependence, clearly is not applicable to the process we have suggested.

In general, the in-falling material will not be strictly in one plane, so that one must permit a range of planes rather than operate strictly close to the equatorial plane,  $\theta = \pi/2$ . We should then expect a number of disks to be confined around the equatorial plane within a vertical dimension which is some few times  $H$ . A distant observer lying between the extremes will receive the signal with a probability which is a few times  $H/1.5r_0$ , i.e.,  $\sim 10^{-3}$ . Although this is admittedly a

small probability, it does not demand an unduly large number of QSO's in our vicinity for the searchlight effect to operate. Perhaps one should draw an analogy with the synchrotron process, where for a strictly uniform magnetic field the radiation is confined in a plane. This would also make the synchrotron process unlikely unless it is argued that the magnetic field is not uniform but changes direction so that with suitable alignment with respect to an observer the radiation can be received. The searchlight effect likewise does not operate strictly in one plane but in a set of planes with different inclinations to the equatorial plane.

#### §(4): *Conclusion*

Given the existence of highly collapsed objects or black holes, the blue shift described above will play a significant role. It is expected that freely falling matter with some angular momentum relative to the central object will circle the object several times before falling into it. The forward emission from such matter close to the unstable circular orbit will come out of the strong gravitational field and will exhibit a blue shift. This enhancement of energy is at the expense of the kinetic energy of the circulating matter. The shape of the emission continuum spectrum has the form  $\nu^{-1}$ , which has wide applications in astrophysics. We have discussed the case of QSO's as one example. It is worth noting that because of the sensitive dependence of  $\nu$  on  $\epsilon$ , even thermal radiation over a narrow wave band in the infrared in the emitting region, results in a  $\nu^{-1}$ -type spectrum from infrared to ultraviolet, a feature common to many QSO's.

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