ON THE HYPOTHESIS OF EJECTION OF SUPERMASSIVE BLACK HOLES FROM CENTERS OF GALAXIES AND ITS APPLICATION TO QUASAR-GALAXY ASSOCIATIONS

RAMESH CHANDER KAPOOR

Indian Institute of Astrophysics, Bangalore, India

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Abstract. It is argued that accreting supermassive black holes ejected from centers of galaxies are the likely models for the quasars observed in association with galaxies. Also pointed out are the implications of a recent suggestion by Horák (1982) to account for the excess redshifts of such quasars due to a combined effect of peculiar Doppler-motion and the gravitational field.

1. Introduction

The evidence for physical association of some quasars with galaxies has been presented by Arp for quite some time now (see Burbidge, 1981, for a review). According to Arp, such quasars have been ejected from the centers of the galaxies they are seen in association with. This, however, has given rise to a controversy because such quasars in almost all cases show up with a redshift in excess over that of the associated galaxy. Quite a few models are now available attempting to explain Arp's observations. The various kinds of objects that can be ejected from a galactic nucleus as a consequence of different ejecting mechanisms proposed in the literature also are those generally invoked for these to be identified with the central power house of quasars and/or radio sources. These include, for instance, superdense bodies (Ambartsumyan, 1958), supermassive rotating magnetoid (Shklovsky, 1972), massive object/black hole (Rees and Saslaw, 1975; Harrison, 1977) supermassive black hole (Kapoor, 1976a, b) and white hole (Narlikar and Das, 1980). Each of these works involves a different ejecting mechanism.

In a previous paper (Kapoor, 1976; hereafter referred to as Paper I), it was proposed that a supermassive black hole may recoil, as soon as it forms, from the nucleus of a galaxy with appreciable speed. This recoil is due to anisotropic emission of gravitational waves radiated in the nonspherical gravitational collapse of the central region of the Galaxy. It captures a large number of stars while on its way out. As the star system bound to the black hole is very dense, violent physical processes between stars can release a large amount of gas which leads to the formation of an accretion disk around the black hole and render it luminous. This phenomenon can serve to explain the observed quasar-galaxy associations. Following Paper I and earlier work (Horák, 1979), Horák (1982) has recently tried to resolve the redshift anomaly by suggesting that the excess redshift of the quasar is due to its peculiar Doppler motion and gravitational redshift.

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The purpose of this paper is to emphasize the viability of a supermassive black hole model for the quasars to explain Arp's observations of quasar-galaxy associations and to point out the ambiguity in the interpretation proposed by Horák (1982) of the observed excess redshift. For the purpose of illustration, we shall confine ourselves to single ejections and to the most important features of the ejected quasars.

2. A Black Hole Model for the Ejected Quasar

We first briefly recall the various models (other than the supermassive black-hole model of Paper I) proposed for ejected quasars and point out that in most cases the magnetoid spinar or a massive object will collapse to become black hole by the time it emerges out of the Galaxy. Here it is appropriate to mention the work of Arp *et al.* (1975) on the isophotal tracings of some of the Galaxies ejecting quasars which reveals disturbances in the inner isophotes extended fairly close in the direction of the quasar. The disturbances are understood to result from tidal interaction between the quasar and the Galaxy. Therefore, if Arp's contention is to be taken seriously, one expects the ejected quasar to be supermassive so as to be able to produce noticeable perturbations in the structure of the Galaxy while on its way out. The time of flight of the ejected object, invoked to represent the quasar, through the Galaxy works out to be $\sim 10^{7-8}$ yr (Kapoor, 1976b). It is therefore conceivable that such an object may collapse by the time it emerges out of the Galaxy, given an initial large, but reasonable, speed of ejection, say, $\gtrsim 10^3$ km s^{-1}. By virtue of the tidal interaction between the Galaxy and the object and the latter's rotation and magnetic field, the collapse is likely to be nonspherical. This should lead to the formation of a black hole that recoils as a consequence of anisotropic emission of gravitational waves accompanying the collapse. However, because of the randomness of the direction of recoil, it is doubtful whether the black hole would at all emerge out of the Galaxy. Furthermore if the black hole does emerge, it is unlikely to have sufficient fuel so as to be observable at the time of its emergence (Kapoor, 1976b).

Another factor that is ignored in most hypotheses interpreting quasar-galaxy associations in terms of ejection of a supermassive object ($\sim 10^9 M_\odot$) from the center of the Galaxy is the accretion of the order of $\sim 10^{8-9}$ galactic stars (and gas). Consequently, a very dense stellar system should form around the central object leading to violent physical processes among the stars and producing features similar to those seen in active galactic nuclei. Such processes would tend to mask the characteristic features of the object itself. Now, so far as activity is concerned, one finds a smooth continuation from active galactic nuclei to quasars; hence, the above is a desirable feature which such hypotheses apparently overlook or do not make allowance for.

An explanation for quasars observed in association with the respective nearby Galaxies in terms of accreting supermassive black holes ejected from the centers of the former is therefore attractive from this point of view (Kapoor, 1976a, b). According to the hypothesis advanced in Paper I, the supermassive black hole, when it forms in the nonspherical gravitational collapse of a supermassive body (coherent mass or a dense cluster) originally located at the center of the Galaxy, is ejected at a speed **V** from there due to anisotropic emission of gravitational waves. On its way out, it captures a large number of stars and gas, given by

$$N \sim \frac{\pi R_s^2 n_0 \alpha}{\beta^4} , \tag{1}$$

where R_s is the Schwarzschild radius of the black hole ($= 2GM/c^2$), n_0 the central density of the Galaxy, α its scale height, and $\beta = V/c$. For $n_0 \sim 10^6$ pc^{-3}, $\alpha \sim 1$ kpc, $\beta \sim 10^{-2}$, we have $N \sim 10^{8-9}$*. The stellar system forming around the black hole is confined within a radius

$$R \sim \frac{2GM}{V^2} ; \tag{2}$$

and, therefore, turns out to be very dense. Violent physical interactions among stars and between stars and the black hole release vast amount of gas leading to the formation of an accretion disk round the black hole at the center. Consequently, the black hole can be luminous enough to be observable by the time it emerges out of the Galaxy. The radiation is expected to have a power law spectrum resembling that from quasars. It is therefore reasonable to ask whether the observed quasar-galaxy associations can be identified with such a phenomenon.

This kind of model need not involve very large or relativistic speeds of ejection. Here we wish to mention that the presumed speed of ejection of the black hole as high as $\sim 10^3$ km s^{-1} is somewhat on a higher side. Recoils with lesser speeds, comparatively more probable, would however, be arrested fast due to overwhelming gravity of the Galaxy and dynamical friction. We suggest this to be identified with the Galaxies showing multiple, split or displaced nuclei. This aspect of the hypothesis is under investigation at present.

Our hypothesis conforms with the present thinking that quasars are supermassive black holes sitting at the centers of Galaxies and rendered luminous (luminosity $\sim 10^{47}$ erg s^{-1}) by the infall of vast amount of gas released in violent physical processes such as stellar tidal disruption, collisions, etc., going on in its vicinity (see, e.g., review by Rees, 1978). A desirable feature of the hypothesis is a mass of $\sim 10^9 M_\odot$ for the black hole, so that it can capture enough fuel during its motion, apart from causing noticeable perturbations. On this ground, hypotheses ejecting massive black holes (mass $\sim 10^5 M_\odot$) do not seem to be viable. In the absence of the operation of loss cone mechanism which works for masses $\lesssim 3 \times 10^8 M_\odot$ (Rees, 1978), the black hole in our case would be less active, and therefore underluminous by several orders of magnitude compared to the Eddington luminosity for its mass. This poses no problem, for, it fits well into Arp's scheme, where, for the distance of a quasar-galaxy pair read from Z_{galaxy} ($= Z_{\text{cosmological}}$), the observed fluxes of the quasar imply a luminosity $\sim 10^{42-43}$ erg s^{-1} only. The present hypothesis suggests that most of the stars are

* In Paper I, N was underestimated.

captured by the black hole during its flight within one scale height of the Galaxy from its center. Therefore, it might seem that the abundance of various elements in the emergent 'object' would be those contributed by the stars belonging to Population II. On the other hand, spectroscopic analyses reveal the field quasars to be very much like solar neighbourhood in abundances, and observationally, quasars seen in association with galaxies do not seem to be any different from field quasars in this respect. However, this is not a serious problem as our hypothesis allows for explosive nucleosynthesis to take place on a reasonable scale during the flight of the black hole and its star system in which, by virtue of stellar coalescences and accretion, massive stars can form and lead eventually to a chain of supernova explosions. Hence, enrichment of emission regions of the 'object' with metals is a distinct possibility.

3. The Redshift Anomaly

We now demonstrate the drawback in the interpretation proposed by Horák (1982) for the observed excess redshift of the quasar (Z_q) over that of the Galaxy. (It is generally believed that the redshift of the Galaxy represents the actual distance to the quasar-galaxy pair.)

Following Paper I and the earlier work (Horák, 1979), Horák (1982) has recently made an attempt to understand the excess redshift of Mark 205 over that of its companion galaxy NGC 4319 by regarding frequency shift in radiation of the quasar as a combined effect of its peculiar Doppler motion and gravitational field. In Paper I, it was pointed out that the redshift anomaly can not be resolved even by considering the net redshift of the ejected 'object' (black hole with an accretion disk and star system) to consist of cosmological (Z_c), common to the quasar and the Galaxy, Doppler (Z_d) and gravitational (Z_g) components – i.e.,

$$1 + Z_q = (1 + Z_c)(1 + Z_d)(1 + Z_g) . \quad (3)$$

The contribution coming from the Doppler effect can be negative and is not of much use. For ejections away from the observer at speed $\sim 10^3$ km s^{-1}, the positive contribution from Doppler effect is too little. One does not know whether gravitational recoil with very large speeds ($\gtrsim 10^5$ km s^{-1}) is likely and even if it takes place, the black hole will not be able to capture enough fuel. Another problem in the Doppler interpretation is Strittmatter's prediction of a large excess of blueshifted objects over the redshifted ones (Burbidge and Burbidge, 1967). To avoid this difficulty, one must have recourse to Hoyle's idea of emission by the quasar in a backward cone, explored in detail by Narlikar and Edmunds (1981). This, however, cannot be accomodated into our picture as of now.

One therefore turns to the gravitational redshift. To obtain a large redshift, most of emission must originate from the regions close to the event horizon of the black hole, which is allowed by standard accretion disk theories. Horák's analysis (Horák, 1982) attributing excess redshift in part to the general relativistic effect can be meaningful only for continuum radiation rather than line emission. The argument of Greenstein and

Schmidt (1964) about the smearing out of any line emission due to a steep gravitational potential is well known. The line width and shell thickness are related as

$$\frac{W}{\Delta\lambda} = \frac{\Delta a}{a} ,$$

where volume of emission is $4\pi a^2 \Delta a$. Here we wish to point out that a calculation of gravitational redshift (Z_g) in radiation of a particle at a distance **a** from the center of a Schwarzschild black hole from the standard equation

$$1 + Z_g = \left(1 - \frac{R_s}{a}\right)^{-1/2} \tag{4}$$

does not take into account the motion of the emitting particle orbiting the black hole. A more suitable form (which also justifies Greenstein and Schmidt's conclusion) is given by Kapoor (1981). Consider a particle emitting monochromatic radiation occupying a compact orbit at $r = a$ ($> 1.5R_s$) from the center of the black hole. The frequency shift (red/blue) and the gravitational bending of its radiation depends sensitively on the angle at which the photon is emitted with respect to the radius vector of the particle through the center of the black hole. This gives rise to an interesting effect: namely, spectral line broadening in the case of a stellar mass black hole and peculiar oscillations of a number of emission lines across the spectrum in the case of a supermassive black hole. In the latter case, when an ensemble of particles occupies a given orbit $r = a$, that is to say, a ring ($\Delta a \to 0$), one will naturally receive a broadened line emission. The wings of the line correspond to tangential back and forward emission causing maximum redshift (Z_{red}) and blue shift (Z_{blue}). The separation of the wings is given (Kapoor, 1981) by

$$Z_{\text{red}} - Z_{\text{blue}} = \Delta Z = 2\left[\frac{R_s a}{(2a - 3R_s)(a - R_s)}\right]^{1/2} . \tag{5}$$

If $a \simeq 9R_s$ – a case considered by Horák (1982) – and, for $\lambda_0 = 5000$ Å, the line-width $W = \Delta Z \lambda_0$ amounts to 2740 Å – a value too large from quasar spectral standards. The line profile is asymmetrical as a consequence of Liouville's theorem; the intensity ratio for the wings being: $I_{\text{blue}}/I_{\text{red}} \simeq 4$. The line center corresponds to radial emission (i.e., along line of sight) and is redshifted from λ_0 by an amount

$$1 + Z_g = \left(1 - \frac{3R_s}{2a}\right)^{-1/2} , \tag{6}$$

giving $Z_g \simeq 0.1$. If one allows for shell thickness (which means, radiating particles are located within $a - \Delta a/2$ and $a + \Delta a/2$) line will be wider still. If one were to suppose that line formation takes place at larger distances, say, at the accretion radius of the black hole

$$r_a = \frac{2GM}{\langle v^2 \rangle} ,$$

where $\langle v^2 \rangle$ is the mean square velocity of stars in the Galaxy, Equation (5) gives

$$\Delta Z \approx \left(\frac{2 \langle v^2 \rangle}{c^2} \right)^{1/2} ; \tag{7}$$

so that $W = 10$ Å approximately; a perfectly sharp line, gravitationally redshifted by an amount

$$Z_g \approx \frac{3 \langle v^2 \rangle}{4c^2} \approx 10^{-6} . \tag{8}$$

Thus these values of W and Z_g are very small to explain quasar line width and excess redshift, and allowance for shell thickness does not help any further (one must have appropriate shell thickness to explain observed fluxes in spectral lines for a given emissivity). Therefore, it is easy to see that Horák's claim falls short of explaining a crucial observational feature of the quasar-galaxy associations: namely, the excess redshift.

A sizeable amount of general relativistic redshift in line emission has been found only in the model of quasars originally proposed by Hoyle and Fowler (1967) and explored in detail by Das and Narlikar (1975). In this model, line emission is produced by a cloud at the center of a compact cluster of collapsed stars. However, details of the ejection mechanism in this model are yet to be worked out.

4. Conclusion

In this paper we have discussed the implications of an accreting supermassive black hole model proposed by us for quasars which, according to Arp,have been ejected from the centers of respective nearby galaxies. We have shown that if the black hole is supermassive, the model can explain the gross features of the quasars such as luminosity, spectrum, metal abundances, and can cause perturbations in the Galaxy as observed. The only unexplained feature is a satisfactory explanation for the excess redshift of the quasars by any of the known physical processes. We find that attempts to explain the excess redshift by invoking peculiar Doppler motion of the object and its gravitational field are not viable answers to the problem.

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