EFFECT OF DYNAMICAL FRICTION ON THE ESCAPE OF A
SUPERMASSIVE BLACK HOLE FROM A GALAXY

RAMESH CHANDER KAPOOR
Indian Institute of Astrophysics, Bangalore, India

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Abstract. We have used the impulsive approximation technique to numerically estimate the effect of dynamical friction on the motion of a supermassive black hole (mass \( \approx 10^9 M_\odot \)) through a galaxy (mass = \( 10^{11} M_\odot \)) which has recoiled from the center of the latter as a result of anisotropic emission of gravitational radiation or asymmetric plasma emission. We find the effect to be minimal for recoil taking place at a velocity larger than that of escape at the center of the galaxy. There is a certain critical velocity of ejection (slightly larger than the central escape velocity) at which the black hole must be ejected for the recoil to be successful. Otherwise, dynamical friction becomes relatively pronounced and damped oscillatory motion of the black hole in the potential well of the galaxy ensues. The phenomenon of high-velocity recoil although rare, can be astrophysically spectacular in view of the fact that the black hole would carry a substantial amount of gaseous material as well as a very large number of galactic stars. Some recent observations are cited where the recoil phenomenon might be applicable.

1. Introduction

It has been suggested by several authors that ejection of matter from galactic nuclei in the form of compact supermassive bodies: namely, magnetoid, spinar, black hole, and white hole can explain certain high-energy phenomena such as relativistic and non-relativistic jets, radio lobes, and quasar-galaxy associations, etc. (Shklovsky, 1972, 1982; Rees and Saslaw, 1975; Kapoor, 1976; Harrison, 1977; Narlikar, 1984, and references quoted therein). The phenomenon of high-velocity recoil is of astrophysical and stellar dynamical interest in many ways. In this paper, we deal with one aspect of the problem, viz., the ejection of a supermassive black hole (mass \( \approx 10^9 M_\odot \)) at velocities comparable to that of escape at the center of the ejecting galaxy (mass \( \approx 10^{11} M_\odot \)) and its tidal interaction with the latter using the impulsive approximation technique as developed by Alladin (1965) for the study of inter-penetrating collisions of galaxies.

The ejection of the supermassive object is achieved by requiring conservation of linear momentum in most of the processes discussed by the authors cited above. For example, the gravitational sling-shot mechanism is fairly efficient in ejecting supermassive black holes and spinars in singles and in pairs (Valtonen, 1977, 1979). Following Bekenstein (1973), Kapoor (1976) has proposed recoil of a supermassive black hole formed in the nonspherical collapse of a supermassive body in a galactic nucleus as a consequence of anisotropic emission of gravitational radiation. Another scenario for ejection in a similar way invokes supermassive black hole binaries in orbit round each other in some active galactic nuclei proposed to explain the observed bending and apparent precession of radio jets emanating from these objects (Begelman et al., 1980). The binary may form from fragmentation in the collapsing mass caused by rotation or from galactic mergers.
which eventually evolves to the stage when the black holes coalesce into a single black hole. The latter would recoil due to anisotropically emitted gravitational wave burst (Rees referred to in Blandford, 1979; see also Cooperstock, 1977). Ejection may also result from asymmetric accretion onto a supermassive black hole, or asymmetric radiation from a spinar or magnetoid in a galactic nucleus (Shklovsky, 1972; Harrison, 1977). Rees (1982) has mentioned that if one-sidedness of jets of compact radio sources is intrinsic, a flip-flop mechanism is needed to give rise to symmetric double radio-lobes. This may, for instance, be achieved if the central engine has been displaced from the center of the galaxy and oscillates in its potential well. Shklovsky (1982) regards one-sidedness of jets of active galactic nuclei in most cases intrinsic, and interprets these as a relativistic ejection of massive plasma clouds (the plasmoids) from thick accretion disks around supermassive black holes in an asymmetric manner. The black hole recoils in the process. Successive plasmoid ejections build up the recoil to the extent that the accreting black hole can escape from the nucleus.

It is relevant to cite here some observations to which the ejection scenario can be applicable. The deep CCD images of the field around the quasar 3C273 obtained by Tyson et al. (1982) reveal an elliptical nebulosity which appears to have an offset location (equivalent to ~ 4 kiloparsecs) from the quasar position. It is less likely to have been caused by the superposition of a galaxy in front, or, by stochastic perturbations of galactic stars in the nucleus of galaxy hosting the quasar (Guzadyan, 1982). Arp et al. (1975) have presented evidence for disturbances in the inner isophotes of some galaxies pointing in the direction of quasars they are seen near, which, in the case of Mkn 205, extend down to the nucleus of NGC 4319 (Sulentic, 1983). The disturbances are indicative of gravitational influence of a supermassive body that presumably has been ejected from the center of the galaxy in question. Fricke et al. (1983) have recently detected a jet-like feature in the outer regions of Seyfert I galaxy Mkn 335, which resembles a weak Seyfert nucleus and could be a consequence of ejection. Wilson et al. (1983) have reported the kinematic center of the rotation curve of the Seyfert and X-ray galaxy NGC 2110 displaced by ~ 230 pc from the active nucleus which in their opinion could be orbiting about or oscillating through the kinematic center of the galaxy.

2. The Ejection and Visibility of the Black Hole

Before we present our calculations regarding the tidal interaction between the black hole and the galaxy, we briefly state the visibility of the recoil phenomenon, assuming that a $V \, dM/dt$ term does not contribute to the equations of motion. It is, therefore, appropriate to first outline the simple gravitational interaction between the black hole and the galaxy. We regard the latter as a Plummer sphere, a model that has been frequently used to represent density distribution in globular clusters, galaxies, and clusters of galaxies (see, e.g., Toomre, 1977). Except for a high-density cusp in the innermost regions, a general mass and density distribution according to this model is of the form

\[ M_1(r) = M_1 \left( \frac{r}{\alpha} \right)^3 \left[ 1 + \frac{r^2}{\alpha^2} \right]^{-3/2}, \quad n(r) = n_0 \left[ 1 + \frac{r^2}{\alpha^2} \right]^{-5/2}, \quad (1) \]