DYNAMICAL FRICTION AND THE ESCAPE OF A COMPACT SUPERMASSIVE OBJECT SHOT FROM THE CENTER OF A GALAXY

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Abstract. A numerical study has been made of the motion of a compact object consisting of a supermassive black hole with a dense cluster of stars around through a galaxy which has recoiled from the center of the latter as a result of anisotropic emission of gravitational radiation or asymmetrical plasma emission. We find that the effect of dynamical friction on its motion through the galaxy (mass \( \sim 10^{11} M_\odot \)) estimated using the impulsive approximation technique, is minimal for an object mass \( \sim 10^9 M_\odot \) and for recoil taking place at a velocity larger than that of escape. A velocity \( \sim 1.1 \) times the escape velocity is needed for the object to escape from the galaxy, whereas for velocities of recoil less than this critical velocity, damped oscillatory motion ensures. The energy exchange of the object with the galaxy is not large enough to cause appreciable change in the internal energy of the latter.

1. Introduction

Various arguments suggest that supermassive black holes should exist in the nuclei of galaxies that have undergone a violent active phase in their life (see Rees, 1984, for a review). The possibility of displacement or ejection of such a black hole from the galaxy's centre has been suggested by many workers (see Kapoor, 1985a, for references). Such a possibility is relevant to models of quasars which are thought to be extreme examples of active galactic nuclei, and jets, because there are several ways in which a supermassive black hole could acquire a high velocity (via gravitational wave recoil, one-sided jets, etc.). One then would like to know whether they then escape from the galaxy, or undergo damped oscillatory motion even if ejected at velocities large compared to that of escape, or are placed in a spiralling orbit, to eventually settle down in the center of the galaxy.

In previous papers (Kapoor, 1985a, b) we have dealt with one aspect of the problem, namely the ejection of a supermassive black hole (\( \sim 10^9 M_\odot \)) at velocities comparable to that of escape at the center of the ejecting galaxy (mass \( \sim 10^{11} M_\odot \)) and its tidal interaction with the latter using the impulsive approximation technique as developed by Alladin (1965) for the study of interpenetrating collisions of galaxies. In this study, the system was idealized as a point mass interacting with the galaxy. It is, however, likely that the black hole would be surrounded by a compact cluster of a large number of stars, provided a high density cusp in the galactic nucleus has developed before the ejecting mechanism could become operative to displace the object from the center of the galaxy. In this paper, we present results of a numerical study of the tidal interaction which incorporates the structural details of the stellar system around the black hole. These calculations might have bearing on a number of observations where movement or
displacement of the central engine is suggested, such as those relating to 3C 84 (Readhead et al., 1983), Mkn 335 (Fricke et al., 1983) and Mkn 205–NGC 4319 (Sulentic, 1983).

2. Tidal Interaction Between the Object and the Galaxy

Most of the hypotheses proposing ejection of the supermassive central component of the galaxy achieve this by requiring conservation of linear momentum. Given this, the tidal interaction between the ejecting galaxy and the ejected object can be studied using the impulsive approximation. Though reasonable, the limitation of the approximation restricts us to velocities of ejection \(V_0\) of the order of or more than the velocity of escape at the centre of the galaxy \(V_{esc}(0)\). Large velocities of interest here would be possible only in an extreme situation.

The galaxy is represented by a Plummer sphere with a density distribution of the form

\[
n_1(r) = n_0 \left[ 1 + \frac{r^2}{x_1^2} \right]^{-5/2},
\]

where \(x_1 = (3M_1/4\pi m_0)\) is the scale length of the system. The potential function for the galaxy is

\[
\phi_1(r) = -\frac{GM_1}{x_1} \left( 1 + \frac{r^2}{x_1^2} \right)^{-1/2},
\]

with an internal energy

\[
U_1 = -\frac{3\pi}{32} \frac{GM_1^2}{x_1}.
\]

It is necessary to specify the density distribution in the object, i.e., in the star system around the black hole. A reasonable representation for the density distribution in the system is an isothermal distribution of stars, each of mass \(m\), which is loaded with a Newtonian singularity of mass \(M_2\) (Huntley and Saslaw, 1975) and which we truncate at the accretion radius \(r_a\) of the black hole

\[
\rho(r) = \lambda \exp \left[ -\frac{\beta x_2 (r-r_{\min})}{rr_{\min}} \right],
\]

\[
r_{\min} \leq r \leq r_a = \frac{2GM_2}{\langle V^2 \rangle}.
\]

In Equation (4), \(\lambda\) is the central density; \(x_2\), the scale length; and \(r_{\min}\) is a certain inner radius of the stellar distribution where for \(r < r_{\min}\), the distribution of stellar velocities is highly anisotropic and not represented by a scalar pressure. For \(r > r_{\min}\) the velocities become more nearly isotropic and are closer to virial equilibrium. Following Huntley