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Central engine or locomotive?*

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Abstract. The astrophysical aspects of proposals of escape of supermassive blackholes from galactic nuclei and their implications in relation to quasars are discussed. We conclude that high velocity recoil of the central engine can at best be considered an exception rather than a rule since it requires a violent release of mass energy in an asymmetrical manner, spectacular in nature. However, scope for the concept of low velocity motion in the inner regions of the host galaxy exists in view of some recent observations.

Key words : quasars—blackhole models—dynamical friction

1. Introduction

The standard picture of quasars today involves a supermassive blackhole at the centre of galaxy surrounded by a disc or torus and a cluster of stars referred to as the central engine (Rees 1984; Wiita 1985). The possibility of displacement or ejection of the central engine which could be a blackhole, a spinar, a white hole or a magnetoid from the centre of the host galaxy has also been suggested from time to time by many workers with a view to explaining such diverse high energy phenomena as relativistic and nonrelativistic jets, radio lobes and quasar-galaxy associations (Shklovsky 1972, 1982; Valtonen 1979; Kapoor 1976, 1985; Narlikar 1984 and references).

Although some of these explanations have since been found inadequate, a few recent observations seem to suggest a revival of this idea where we might be dealing with a central engine displaced from or in motion with respect to the kinematic centre of the galaxy. The deep CCD images of the field around the quasar 3C 273, for example, reveal an elliptical nebulosity which appears to have an offset location, $\simeq$ 4 kpc, from the quasar position (Tyson, Baum & Kreidl 1983). These authors discount the possibility that the asymmetric location is caused by the superposition of a galaxy in front. Further, it is not likely to be due to stochastic perturbations of stars in the nucleus of the host galaxy either (Gurzadyan 1982). Then, there

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are the debated observations by Arp, Pratt & Sulentic (1975) indicating disturbances in the inner isophotes of some galaxies pointing in the direction of quasars they are seen near, which in the case of the quasar-galaxy system Mkn 205-NGC 4319 extend down to the nucleus of the associated galaxy (Sulentic 1983). The disturbances could have been caused by a supermassive body presumably ejected from the centre of the galaxy. Recently, Fricke, Kollatschny & Schleicher (1983) have detected a jet-like feature in the outer regions of the Seyfert 1 galaxy Mkn 335. This feature resembles a weak Seyfert nucleus and could be a consequence of ejection. There is the evidence of displacement by $\simeq$ 230 pc of the kinetic centre of the rotation curve of the Seyfert and x-ray galaxy NGC 2110 from the active nucleus which could be orbiting about or oscillating through the potential well of the galaxy (Wilson *et al.* 1983). Certain features of the observations of 3C 84 made by Readhead *et al.* (1983) at 22.4 GHz call for an explanation in terms of the motion of the central engine away from the dynamical centre of the galaxy. At a smaller scale, a similar kind of movement is proposed by Bertol & Sharp (1984) in the case of NGC 3310 also.

In view of these observations it is relevant to explore some of the astrophysical implications of the idea of a high velocity motion of the central engine. It is the purpose of this essay to address this issue.

Theoretically, a number of physical processes exist that will impart a net velocity from a few tens of km s^{-1} to thousands of km s^{-1} to the compact supermassive object in a galactic nucleus. Should this happen, one would like to know whether the object then escapes from the galaxy or undergoes an oscillatory motion damped by dynamical friction even if ejected at a velocity large in comparison to that of escape, or, is placed in a spiralling orbit, to eventually settle down in the centre of the galaxy. The ejection of the object is achieved by requiring conservation of linear momentum. For instance, a process like gravitational sling-shot or asymmetrical emission of plasma or radiation (electromagnetic/gravitational) can produce large velocities (Shklovsky 1972, 1982; Kapoor 1976; Valtonen 1979). Rees (1982) remarks 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 centre of the galaxy and oscillates in its potential well. The work of Wiita & Siah (1981) indicates that the central engine, orbiting or displaced from the centre of mass of a confining gas cloud, *can* provide a flip-flop behaviour where essentially similar but oppositely directed beams are active only one at a time.

Whereas physical one-sided jets definitely seem to exist in some sources (Saikia & Wiita 1982), Shklovsky (1982) regarded one-sidedness of jets of active galactic nuclei in most cases as intrinsic and interpreted these as a relativistic ejection of massive plasma clouds (plasmoids) from thick accretion discs in an asymmetric manner. The blackhole recoils in the process. Successive plasmoid ejections build up the recoil to the extent ($V_H \simeq 10^4$ km s^{-1}) that the accreting supermassive blackhole ($M_H \simeq 10^9 M_\odot$) is pushed out of the nucleus. (Subscript H refers to the blackhole). According to Shklovsky (1982), the fuel carried by the blackhole would not last for the time of flight $\tau \sim R/V_H$ (R being the dimension of the galaxy) and the quasar must be extinguished even before it comes out of the galaxy. Evolutionary effects imply that almost every galactic nucleus contains a defunct quasar. If the quasar has escaped from the nucleus of the galaxy, the problem of explaining evolutionary effects is solved according to the above scenario.

2. The escape and its implications

An important aspect not stressed in the ejection scenarios is the accretion of matter by the compact object in motion and its visibility over the duration comparable to the flight time. The ejection phenomenon can be spectacular if one considers the ejected blackhole to be supermassive ($\sim 10^8$–$10^9\, M_\odot$) since it would then be able to carry as well as capture a large number of galactic stars, provided a density cusp in the galactic nucleus has developed prior to the ejection. In such a case, material around the blackhole which can be in the form of an accretion disc (or torus), gas clouds and a dense cluster of stars is bound to it gravitationally within a volume of dimension $r_a \sim 2GM_H/\langle V^2\rangle$, $\langle V^2\rangle$ being the mean square velocity of stars. When the recoil takes place (or builds up sufficiently), material within a volume of dimension $r_c \sim 2GM_H/(V_H^2 + \langle V^2\rangle)$ is carried along. If most of this mass is in the form of stars, their number is roughly $N_1 \sim \frac{4}{3}\pi r_c^3 n_0$ which is $\sim 10^8$ if n_0, the central star density of the galaxy, is $\sim 10^5$ pc^{-3}. Further, mass of the accretion disc M_g itself could be of similar order. However, these quantities are model dependent To ensure that recoil takes place $(mN_1 + M_g) < M_H$ (Kapoor 1985). In general, the blackhole captures galactic stars also while on its way out, a quantitative expression for which is (Kapoor 1976)

$$N_2 \sim \int n(r)\, \sigma_{\rm cap}(r)\, dr \simeq \frac{16\pi G^2 M_H^2 n_0 r_0}{V_H^2 c^2}, \qquad \ldots(1)$$

where $\sigma_{\rm cap}$ refers to the capture cross-section ($\leqslant \pi r_c^2$) for nonrelativistic particles mass ($m \leqslant M_H$) falling into the hole from infinity in the hole's frame. Substantial captures take place over distances $r_0 \sim r_c$ ($\sim$ 10 pc) from the centre of the galaxy so that we find $N_2 \sim 10^{4-5}$ which is rather small. It may be argued that the blackhole should catapult galactic stars passing within a distance $\sim r_c$ of its trajectory, in the direction of its motion in the reference frame of the galaxy. However, it is possible that a star may be captured from within a distance $\sim r_c$ also by interacting with collective modes of the cluster around the blackhole, rather than requiring just a 3-body interaction. According to W. C. Saslaw (personal communication), many-body modes of capture may be significant at low velocity—a process intermediate between the 3-body captures and dynamical friction. In the situation under consideration here, when the blackhole moves a distance beyond $\sim r_0$ from the centre of the galaxy, the stellar density drops to the extent that such captures or accelerations will be virtually incapable of reducing the linear momentum of the hole or lead to any significant observable effects other than possibly showing up with an anomalous velocity dispersion along the trajectory. Even the amount of interstellar gas accreted along the path turns out to be $\leqslant M_H$.

Confined to a region of dimension $\lesssim r_c$ around the blackhole, the star system is highly compact, diffused with gaseous debris disrupted from stars coalescing or colliding with others and the tidal interactions between stars and the blackhole. The density is high enough for violent physical processes to keep feeding the blackhole. For $M_H > 3 \times 10^8 M_\odot$, stellar consumption in toto by the blackhole can be very large. Comparing the rate of stellar collisions, $\dot{N}_{\rm coll}$ with that of consumption of stars by the blackhole, $\dot{N}_{\rm cons}$, (Kapoor 1983)

$$\frac{\dot{N}_{\rm coll}}{\dot{N}_{\rm cons}} \approx 4N_1 \left(\frac{R_*}{R_s}\right)^2, \qquad \ldots(2)$$

(R_s = Schwarzschild radius of the blackhole; R_* = mean stellar radius $\sim R_\odot$), we find that for $N_1 \gtrsim 10^6$, the ratio exceeds unity. If in each collision, an average mass $\approx 0.1\ M_\odot$ is released, the entire system liberates mass at a rate $\sim 0.1\ M_\odot\ {\rm yr}^{-1}$. This can maintain the accretion process which at 10% efficiency would radiate $\sim 10^{44}$ erg s^{-1} of energy for a period $\gtrsim 10^7$ yr which exceeds the flight time. The luminosity could be as low as $\sim 10^{41-42}$ erg s^{-1} if it is just a bare blackhole which accretes gas from the interstellar medium while moving through it. It is interesting to note that much of the gaseous remnants of the various physical processes remain bound to the blackhole all through since there is virtually no ram pressure stripping of the gas accreting onto the blackhole while the system passes through the interstellar medium. Also, we find the ram pressure effect to drop as V_H is increased (Kapoor 1983), something contrary to general expectation.

Thus assuming that the quasar is eventually pushed out of the galaxy, we find that it does not go defunct so soon even though its luminosity may be somewhat below the Eddington limit for the mass of the accreting blackhole. Keeping in mind the coherent scattering off the fluctuations in the stellar density produced by the blackhole in its wake (Saslaw 1975), one infers from the equations of motion that the velocity increments $\sum_i \Delta V_i < \langle V^2 \rangle^{1/2}$ kill the recoil statistically, whereas a single increment $\Delta V_i > \langle V^2 \rangle^{1/2}$ would suffice to push the blackhole out of the nucleus. That would require a very powerful asymmetrical release of energy, spectacular in nature. An extragalactic source that has an associated (relativistic/subrelativistic) jet to start with must eventually show up paired with a luminous object.

3. Dynamical friction

To what extent does dynamical friction affect the escapability of a recoiling blackhole ? This for instance can be determined by using the same technique as employed for a study of the interpenetrating collisions of galaxies in an impulsive approximation (Alladin 1965; Kapoor 1985), which has been found to be reasonably useful even at low velocities.

Treating one of the systems as a point mass simplifies this calculation. Assuming the galaxy to be non-rotating and the motion of the blackhole to be only along the z-axis, we write their mutual interaction energy as

$$W(z) = -\,GMM_{\mathrm{H}}\chi(z), \qquad \ldots(3)$$

where

$$\chi(z) = \frac{1}{\alpha(1 + z^2/\alpha^2)^{1/2}},$$

if we treat the galaxy as a Plummer sphere with a scale length α. The blackhole induces a change ΔU in the binding energy of the galaxy. The velocity of the blackhole with respect to the centre of the galaxy can then be written as

$$V(z) = \left\{\frac{2}{\mu}\left[\frac{\mu}{2}\,V_{\mathrm{H}}^2 + W(0) - W(z) - \Delta U(z)\right]\right\}^{1/2}, \qquad \ldots(4)$$

$$\mu = \frac{MM_{\mathrm{H}}}{M + M_{\mathrm{H}}}\,.$$

The quantity $\Delta U(z)$ is estimated thus : we divide the galaxy into twenty shells, characterized by radii a, where $\alpha \leqslant a \leqslant 20\,\alpha = R$. Each shell is defined by 14 stars at locations in the following manner : 6 stars are placed on the axes of the Cartesian coordinates whereas 8 are placed on the centres of octans of the spheres of radius a; thus taking 280 stars, we believe that the galaxy is fairly well approximated. Starting with $z = 0.05\alpha$, we set $\Delta U = 0$ and calculate a mean increase in the kinetic energy of a shell due to the tidal influence of the blackhole while at z. In the impulsive approximation this change equals that in the binding energy. An integration over the mass of the galaxy then gives $\Delta U(z)$. An interation is performed till a converged value of $\Delta U(z)$ is obtained. The effect of dynamical friction on the motion of the blackhole through the galaxy can be inferred by comparing $V(z)$ with $V'(z)$ where $dV'(z)/dt = -\,GM(z)/z^2$. Our calculations reveal the effect of dynamical friction to be minimal, which dwindles as the ejection velocity, V_{H}, is enhanced The recoil must take place at a critical velocity V_{cr}, rather than at $V_{\mathrm{esc}}(z = 0)$ in order to be a successful one. If $M_{\mathrm{H}} = 1.1 \times 10^9\,M_\odot$, $M = 10^{11}\,M_\odot$, we find $V_{\mathrm{cr}} \simeq 1.01\,V_{\mathrm{esc}}(0)$. Value of V_{cr} is revised upwards, to $1.1\,V_{\mathrm{esc}}(0)$, if we take into account the extended nature of the object (*i.e.* blackhole plus the star system bound to it). For this, we can take an isothermal sphere of 10^8 stars around a blackhole, the net mass still being $1.1 \times 10^9\,M_\odot$, and liken the density distribution to that of a loaded isothermal sphere, *à la* Huntley & Saslaw (1975), truncated at the accretion radius r_{a} of the blackhole. The tidal influence of the galaxy on the star system around the blackhole can also be estimated. This turns out to be comparable to that for the galaxy.

In the case of $M_{\mathrm{H}} \gtrsim 10^{10}\,M_\odot$ and $V_{\mathrm{H}} \simeq V_{\mathrm{cr}}$, the tidal influence of the ejected object on the galaxy would be noticeable. But it is not known whether a galaxy would eject 10% of its mass in a coherent form. If $M_{\mathrm{H}} \sim 10^8\,M_\odot$ (or less) which is quite likely, the force of dynamical friction would be less by two (or less) orders of magnitude in comparison with that on a $10^9\,M_\odot$ object. It is interesting to note that the average velocity increment imparted to galactic stars by the object is $\lesssim 1$ km s^{-1} for $V_{\mathrm{H}} \gtrsim V_{\mathrm{cr}}$ so that even an object of mass $10^9\,M_\odot$ will not be able to pull any significant amount of galactic material in its wake. Instead, its track would be delineated by a very faint perturbation in the distribution of stars and gas in its wake, ionizing effects on the interstellar medium, bursts of star formation and hot spots (plasma thrown out at large velocities from the object) leading to a blue gradient with a tendency to steepen towards the ejected object.

For recoil velocities $< V_{\mathrm{cr}}$ the object falls back and would execute a damped oscillatory motion which may last for a fairly large number of oscillations before it could eventually settle in the centre of the galaxy due to secular effect of dynamical friction. The trajectory, however, would progressively be bent by coherent scatterings off the fluctuations in the stellar density the object produces in its wake. If it passes through the nucleus, the fuel supply can be renewed. Low velocity motion of the central engine through the potential well of the galaxy would be relevant in relation to many of the systems cited in section 1, but an N-body treatment of this problem is called for to get a correct picture of the orbital motion of the central engine in the inner regions of the galaxy.

4. Conclusions

We have discussed certain aspects of the motion of a compact supermassive object that is originally at rest at the centre of a typical galaxy and is set in motion by asymmetrical emission of plasma or radiation. We find the ejection phenomenon to be spectacular but with hardly any damage ($| \Delta U/U | \ll 1$) caused to the galaxy of internal energy $| U |$ through tidal influence on it by the supermassive object. Currently available observations suggest that high velocity motion of the central engine should be considered an exception rather than a rule since it would require a highly powerful asymmetrical burst of emission of mass energy. Further, if such an event were a general occurrence, the activity prolonged by accretion (material made available by stellar captures and interstellar gas en route and by accompanying system of stars and gas) would tend to produce a steeper luminosity function for flat spectrum sources. To circumvent this one would then have to place an upper limit on the mass of the supermassive blackhole, say $\lesssim 10^7 M_\odot$, to be pushed out of a galactic nucleus.

For recoils slower than a certain critical velocity which slightly exceeds the central escape velocity by virtue of dynamical friction, damped oscillatory motion ensues, which in turn is compounded by coherent scatterings off the fluctuations in the stellar density in the wake of the object. The object escapes pruning but can renew its fuel supply if it passes through the centre of the galaxy. The scope of the concept of a central engine in motion in the inner regions of the host galaxy is ample in view of the hope that many more systems with characteristics like 3C 84, NGC 2110, NGC 3110 and Mkn 335 will be discovered in the future.

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