A CONSEQUENCE OF THE ASYMMETRY OF JETS IN QUASARS AND ACTIVE NUCLEI OF GALAXIES

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ABSTRACT

It is concluded that many, if not most, jets are truly one-sided. The hypothesis that the powerful radio emission of quasars and radio galaxies is caused by ejections of "plasmoids" originating in super-critical accretion on massive black holes is discussed. Because of asymmetry in the ejection of plasmoids from the thick accretion disks which form around massive black holes, the latter acquire considerable recoil momentum and should escape from the nuclei of the galaxies with large velocities. This provides a possibility for explaining a number of evolutionary effects and an approach to solving the problem of "dead" quasars.

THE REALITY OF ONE-SIDED JETS

Although over 80% of extragalactic sources--radio galaxies and quasars--are double, typically with an optical object lying between two extended radio-emitting clouds, the so-called "jets" emerging from active nuclei usually are "one-sided". The classical example is the famous jet in NGC 4486. In 1968, I suggested an interpretation of this feature as an ejection of compact plasma clouds ("plasmoids") from the nucleus of the galaxy at relativistic velocity and at a small angle to the line of sight (Shklovsky, 1968). I subsequently developed this idea further and applied it to several other objects (Shklovsky 1977, 1980). Scheuer and Readhead (1979) used it in interpreting the superluminal transverse velocities of compact components of several extragalactic radio sources observed by intercontinental interferometry. They advanced the interesting hypothesis that the so-called "radio-loud" quasars differ from the "radio-quiet" quasars only in having a favorable orientation for the direction of ejection of plasmoids moving at relativistic velocities.

It is assumed in all of the above mentioned papers that the plasmoids are ejected in two diametrically opposed directions. Owing

D. S. Heeschen and C. M. Wade (eds.), Extragalactic Radio Sources, 475–481.

to the Doppler effect, at relativistic velocities the flux from a receding component will be sharply reduced and can become unobservable, while the flux from a source approaching the observer is strongly enhanced. There can be no doubt that this effect does occur in nature. Recently, VLBI observations have shown reliably that a plasmoid ejected from the nucleus of 3C 273 has a transverse velocity $V_t \sim 10c$ (Pearson et al., 1981). From this it follows that the ejection occurred at an angle $\sim 6°$ to the line of sight and that its flux was enhanced by several thousand times owing to the Doppler effect. The question then arises: Is the absence of a "counter-jet" always due to a redshift which strongly attenuates the radiation? Do truly one-sided jets exist?

Analysis of the observational data leads us to conclude that one-sided jets do in fact exist.

(a) Cygnus A. A jet ~ 5 pc in length has recently been discovered; its direction differs only 6° from that of the radio axis of the source (Linfield, 1980). No counter-jet as strong as 5% of the jet was found. According to Hargrave and Ryle (1974), the radio axis of Cygnus A lies within 25° of the sky plane. Moreover, Simkin (1977) found that the rotation axis of the Cygnus A galaxy is inclined 6° with respect to the sky plane. This excludes the possibility of explaining the absence of a counter-jet by the relativistic Doppler effect. Linfield (1980) also studied the jets in the radio galaxies 3C 111, 3C 390.3, and 0055+30. One-sided jets were observed in all three cases. The orientations of the radio axes of these galaxies are not known, although in the case of 3C 111 it probably lies close to the sky plane.

(b) A one-sided jet was recently found in the nearest radio galaxy, Centaurus A (Feigelson et al., 1981). It is hard to imagine that the radio axis of NGC 5128 is close to the line of sight, particularly in view of the fact that the second nearest radio galaxy, NGC 4486, should also be "favorably oriented". The probability that the two nearest radio galaxies independently have a special orientation is about 10^{-2}.

(c) Two-sided as well as one-sided jets are observed, as in the radio galaxy Fornax A, where the jets are ~ 1 pc long (Fomalont and Geldzahler, 1980).

Thus, we can say that both one-sided and two-sided jets occur near the active galactic nuclei, and that the one-sided jets appear to occur several times more frequently than the two-sided jets. It can no longer be doubted that the jets are the source of the radio-emitting matter (i.e., relativistic electrons) in the extended clouds symmetrically flanking the optical galaxy. The fact that two such clouds are usually seen, while the nuclear jets are most often one-sided, means that the jets occur sometimes in one direction and sometimes in the diametrically opposite direction.

The time through which the ejection of plasmoids continues in a given direction can be rather long. For example, the one-sided jet from the nucleus of NGC 5128, consisting of several condensations, extends for some 5 kpc, so the duration of the one-sided ejection is at least 15000 years and probably much longer. Near this galaxy two quite asymmetrical intermediate maxima in radio brightness are observed. The center of the northeastern maximum is 23' from the nucleus of the galaxy, while the center of the southwestern maximum is fully 115' away. On the other hand, the "innermost" and "outermost" brightness maxima are very symmetrically placed; their distances from the nucleus are the same, 4' and 190', respectively. It seems most natural to regard the intermediate maxima as having been caused by one-sided jets which occurred at different epochs in the evolution of NGC 5128. With this interpretation of the intermediate maxima, the duration of the one-sided ejections must be reckoned in millions of years.

Finally, let us consider radio component "A" in 3C 273. It lies at the very end of the optical jet and has a diffuse structure; its angular radius at 20 cm wavelength is ~6", which corresponds to a linear size ~50 kpc (Perley et al., 1980). The magnetic field at its periphery is perpendicular to the direction of the jet, as in Cygnus A.

It is natural to regard this component not as an extension of the jet but rather as a feature "fed" by the jet, wholly analogous to the clouds in the double radio galaxies (see Perley et al., 1980). If this is so, the velocity of this component must be definitely non-relativistic. This interpretation raises a question: Where is the second, symmetrically placed, radio cloud 3C 273? According to Perley et al. (1980), some 30% of compact sources (mostly quasars) have components at distances of several arcseconds. These components are optically thin and are distinguished by steep radio spectra ($\alpha \sim 1$). The above authors suggest that in all such cases the objects are like Cygnus A, but with their radio axes lying fairly close to the line of sight. They explain the absence of symmetrical components by projection on the compact components. In this case, however, the spectrum of the well-studied component 3C 273B should show a strong excess of radiation at low frequencies, which certainly is not observed. The absence of the symmetrical component simply means that the jet in 3C 273 is really one-sided (although with relativistic velocity) and that it has remained one-sided throughout the evolution of this quasar, i.e., for several million years.

Thus the ejection of plasmoids is an inherently non-symmetrical event. Since the characteristic time of "one-sidedness" of the activity of nuclei can exceed several million years, and the duration of the radio-emitting phase in galaxies and quasars is of the same order, the overall activity of galactic nuclei (i.e., integrated over the whole time of evolution) is probably an asymmetrical phenomenon.

CAN MASSIVE BLACK HOLES LONG REMAIN IN THE NUCLEI OF GALAXIES?

In §1, we concluded from an analysis of the observational data that many and perhaps most jets are truly one-sided, and that this property is preserved for millions of years. This implies a very important result: Because of the asymmetrical character of the activity, a supermassive black hole can acquire momentum in the direction opposite to the ejection of the plasmoids, i.e., along the axis of the nucleus. With each ejection from the disk of a plasmoid of mass Δm at a velocity $v \sim c$, the black hole receives a small velocity increment

$$\Delta v_1 \sim \frac{\Delta m \cdot c}{M_H} .$$

During the lifetime of the one-sided relativistic ejection, the black hole acquires a recoil velocity

$$v_H \sim \frac{M}{M_H} \cdot c .$$

This effect is entirely similar to the acquisition of added velocity by the center of mass of a binary system where one component has undergone a supernova explosion, when the explosion is not spherically symmetrical. The only difference is that in our case the momentum is acquired gradually. In principal, the effect should be impeded by dynamical friction from all of the stars of the galaxy. This process has been investigated by White (1976), who calculated its characteristic time as

$$t_{df} \sim \frac{1}{30} \frac{M(R)}{M_H} \left[\frac{GM(R)}{R^3}\right]^{-1/2} ,$$

where $M(R)$ is the galactic mass interior to radius R and M_H is the mass of the black hole. In all cases of real interest, however,

$$t_{df} \gg \tau = \frac{R}{V_H} ,$$

where τ is the time which the recoil-accelerated black hole takes to move out of the galaxy.

Consider the specific case of 3C 273, whose jet must be one-sided (see §1). We can estimate the energy of the relativistic particles and the field in component A in the usual way. The calculations can be made by reference to Cygnus A, which has a spectral index similar to that of 3C 273A. The effective angular diameter of each component of Cygnus A is ~30", five times greater than for 3C 273A, while the radio flux from each component of Cygnus A is also 20 times greater. Then the energy in 3C 273A is about two times less than in either component of Cygnus A. We adopt $W \sim 3 \times 10^{59}$ erg. The sole source of this energy is the total kinetic energy E of the jets, so $W \sim \alpha E$. We found from an analysis of the jets in M87 that $\alpha \sim 10^{-2} - 10^{-1}$. The total momentum is

$$P = \frac{W}{\alpha \cdot c} \sim 10^{51} \text{ g cm sec}^{-1} .$$

We assume (rather arbitrarily) that the mass of the black hole in 3C 273 is $\sim 5 \times 10^{8}\ M_{\odot} \sim 10^{49}$ g. It follows that the velocity ultimately attained by the black hole during the course of the activity leading to the formation of 3C 273A is $\sim 10^{9}$ cm sec^{-1}. Moving with this speed for the time which has elapsed since the formation of component A ($\tau \sim 3 \times 10^{6}$ years), the black hole should have moved ~30 kpc from its original place. This means, however, that the black hole has moved far outside the relatively dense part of the parent galaxy (probably spheroidal), and it is not clear how the observed supercritical accretion on it can be continuing!

The contradiction can be circumvented in the following way. We do not doubt the law of conservation of momentum so, if all of the premises we have adopted are correct (one-sided jet, black hole mass $M_H \sim 5 \times 10^{8}\ M_{\odot}$, interpretation of 3C 273A as an object like the components of Cygnus A), black holes must escape from their parent galaxies and accretion on them should drop far below the critical level. Simply stated, they will cease to be compact radio sources. Since in the case of 3C 273B (like in other similar cases) we still observe such a source, the only possible explanation is that it is not the same black hole that gave birth to 3C 273A.

The most general picture that can be drawn at present for the structure of an active galactic nucleus is as follows: In a small (1 - 10 pc) region there is an exceptionally dense ($10^{8} - 10^{11}$ stars) supercluster which contains interstellar gas. In the course of its evolution a massive black hole is formed, around which an accretion disk forms. The plane of this disk is approximately parallel to the symmetry plane of the cluster, which as a rule coincides with the symmetry plane of the galaxy. It is tacitly assumed that a single massive black hole forms in a nucleus. Even with a black hole mass $\sim 10^{8}\ M_{\odot}$ and a velocity of $\sim 3 \times 10^{7}$ cm sec^{-1} for macroscopic motions in the nucleus, however, the sphere of gravitational action of the black hole extends only to ~0.1 pc, much less than the typical dimensions of a nucleus. Therefore, there is no reason why several or even many massive black holes should not simultaneously be present in a nucleus, with approximately parallel accretion disks. At a given time in the active state, for example, there can be one black hole, or there might be more.

In some radio galaxies several more or less symmetrically placed pairs of radio-emitting clouds are observed. The classical example is NGC 5128 (see §1). The usual interpretation of this postulates cycles of activity in a single compact object in the nucleus. One could

https://doi.org/10.1017/S0074180900028448 Published online by Cambridge University Press

equally well, however, hypothesize that different active compact objects are responsible for the various cycles.

The concept of massive black holes escaping from the nuclei of galaxies opens up some interesting new possibilities for interpreting long-known astronomical observations. Let us consider just the problem of the luminosity functions for different kinds of quasars and radio galaxies and features of their evolution. We shall draw on the summary of these problems given by Schmidt (1978).

There is a noteworthy difference between the luminosity functions for quasars with flat and steep spectra. The luminosity function for those with flat spectra is rather flat; for a 100-fold change in radio power, their space density changes by a factor of ~ 30, while the density changes by a factor of ~ 200 for those with steep spectra. We must interpret the quasars with flat spectra as being directly associated with the accretion disks around massive black holes (the prototype is 3C 273B), while those with steep spectra must be analogous to 3C 273A. The latter are structures which are fairly slowly diffusing into the intergalactic medium, their radio luminosities decreasing continually once the "pumping" has ended (compare Cygnus A and Centaurus A, whose energy content W differs by less than an order of magnitude, while their luminosities differ by a factor of several thousand). On the other hand, the power radiated by objects like 3C 273B remains more or less constant so long as supercritical accretion continues. It is determined by the mass of the black hole. Therefore, the luminosity function for sources of 3C 273B type should be similar to the mass function of the corresponding black holes, which must be rather flat.

The most important problem is the difference of the evolutionary effect for the different types of quasars. While the evolutionary effect is very large for the quasars with steep spectra and also for the strong radio galaxies and the radio-quiet quasars (at $z = 1$ their density is about 150 times the local value), it amounts only to a factor of 3 – 4 for quasars with flat spectra (the densities are referred to a co-moving coordinate frame).

In principle, the difference can be explained by the different lifetimes of sources of the two kinds. As has been implied above, quasars with flat spectra must be short-lived. As soon as the super-critically accreting regime ends (as it must when a quasar moves out of the dense nuclear region), the object "goes out". On the other hand, the lifetimes of quasars with steep spectra are much longer, particularly at large z, where the density of the intergalactic medium was much higher than it is locally, making the spreading velocity significantly less than at present.

The idea that black holes escape from galaxies provides a possible approach to solving an important problem of long standing--that of the "dead quasars". It follows from the evolutionary effect that nearly every galactic nucleus should contain an "extinguished" quasar, which cannot be detected in any way. If in fact quasars escape from the nuclei of galaxies, the problem is decisively solved.

It is hardly necessary to point out that the above scenario for the evolution of quasars of different types is highly schematic. Our aim has been to call attention to the important astronomical consequences of the asymmetry of jets.

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