'NOMADIC' NUCLEI OF GALAXIES

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Abstract. In this paper we discuss observational and theoretical arguments in favour of hypothesis on 'nomad life' of active nuclei inside and outside galaxies as well as its consequences. It may be the anisotropic collapse of a supermassive star, or the disruption of a supermassive binary system after the collapse of one companion that would give birth to such nuclei. We predict the existence of veritable quasi-stellar active objects without any ghost galaxies.

Among galaxies showing different forms of activity (radio-galaxies, Seyfert galaxies, host galaxies of quasars, ring galaxies, etc.) we often see an asymmetric nucleus situation in a galaxy. Describing one of these cases – the central radio source shift (800 pc) with respect to the extended radio structure in M87 – Lipunov (1979) proposed a hypothesis that an active nucleus can move in a galaxy. At present we have a lot of observational facts which can be interpreted in terms of such a hypothesis.

1.1

M87 (radio source Virgo A), the central galaxy in the Virgo cluster, is not a unique case of asymmetric situation of a nucleus with respect to the total radio structure of a galaxy. In a recent paper Ulvestad and Wilson (1984) have presented radio-images of a sample of Seyfert galaxies at $\lambda = 6$ cm, about 50% of all galaxies demonstrate such an asymmetry. For example, at $\lambda = 6$ cm the Seyfert galaxy Mkn 273 has a regular double-component structure extended in the NW–SE direction. The optical nucleus does not lie on the line between them. It situates $0\overset{''}{.}5$ (560 pc) to the west from one radio component and $0\overset{''}{.}8$ (900 pc) to the south from other. The authors suggest that this situation is due to the observational uncertainties in radio images as well as in optics and that, in reality, the optical nucleus coincides with one of the components or lies between them. But from their Figure 1 one can conclude that the shift of the optical nucleus with respect to the radio structure is larger than the size of the beam and larger than the mean deviations of the position determination in optics. We cannot be quite sure that, in the case of Mkn 273, the asymmetry of nucleus situation is real; but the fact is that with the symmetry of active galaxies nuclei the situation is very often unclear.

1.2

Now it is quite clear that nebulosities detected around many quasars are galaxies in which quasars play a role of active nuclei. Thus some facts concerning non-central situation of quasars with respect to ghost nebulosities can be explained in terms of

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'nomadic' nuclei of galaxies. Let us consider in detail two low-redshift systems 'quasar-nebulosity' possessing such asymmetry.

(a) The host galaxy of 3C 273, which is one of the nearest quasars ($z = 0.158$), is difficult to study because of the brightness of the quasar itself. To obtain an image of the 3C 273 galaxy Tyson *et al.* (1982) have used a CCD detector in a coronographic camera with a 3″ occulting disk. So they have observed the galaxy *without* the quasar. On the resulting map the occulting disk appears to be shifted from the centre of isophotes of the galaxy 0″.5 (800 pc) to the west. Tyson *et al.* (1982) have not been quite sure that the geometric centre of the occulting disk coincides precisely with the quasar. Probably that is why these authors have not mentioned the asymmetry of the quasar situation in the galaxy among their main results, and have characterized it by the following sentence in the text: "Note, however, that the nebulosity appears to be offset (to east) from the quasar position, even in the raw data in Figure 1." This was enough for Chitre *et al.* (1984) to accept the asymmetry of the quasar situation in the galaxy as a well-established fact. They have used this fact to argue that in the case of 3C 273 we deal with a gravitationally-lensed quasar, and the nebulosity observed by Tyson *et al.* (1982) is an intervening galaxy at intermediate redshift. But they have not taken into account results of Wyckoff *et al.* (1980) who obtained nebulosity spectrum and have identified three emission lines at the redshift exactly coincided with that of the quasar. So the fact that the galaxy is associated with the quasar seems evident. But the non-central situation of the quasar in the galaxy has not been definitively established by Tyson *et al.* (1982). However, new data have been published recently which may serve as indirect evidences that the nucleus of the galaxy has left its place in the centre of the galaxy. Boroson and Oke (1984) have obtained spectra of the galaxy for several points. Emission lines to the east of the quasar (where the quasar would be to situate some time ago) appear to be more intense than at the other points of the nebulosity. Thus the asymmetry of the 3C 273 image obtained by Tyson *et al.* (1982) is confirmed by the asymmetry of the nebulosity spectral properties obtained by Boroson and Oke (1984).

But the main results of these works contradict each other: Tyson *et al.* (1982) classify the 3C 273 galaxy as a giant elliptical ($M_V = -22.5$, a red colour – the galaxy was not detected with a blue filter), Boroson and Oke's (1984) results ($M_V = -21.5$, $B - V = 0.5$) argue in favour of late type of the galaxy. The presence of stars, not only a gas, in the nebulosity is confirmed by detection of the Mg I b $\lambda 5175$ Å absorption line in the spectra at the redshift of the quasar (Boroson and Oke, 1984).

(b) 3C 48 is another quasar situated eccentrically with respect to the associated nebulosity. This quasar was studied twenty years ago – without any isophotal image, only by visual analysis of plates. On a plate sensitive to the red Matthews and Sandage (1963) have detected a nebulosity: an oval elongated in the north–south direction with dimensions 12″ × 5″. The quasar is offset 3″ (16 kpc assuming $H = 100$ km s^{-1} Mpc^{-1}) to the south from the centre of the nebulosity. In 1966 the nebulosity was photographied once more by Sandage and Miller (1966). Using their plate Wampler *et al.* (1975) conclude that the nebulosity extend 5″.25 to the north and 4″ to the south from the quasar. From these values we can derive only 0″.6 (3 kpc) shift of the quasar to the south from the centre of the nebulosity. As isophotes were not drawn and as two photo images were obtained under different conditions, this discrepancy of the shift values was not unexpected. The fact that both the studies shows the shift of the quasar in the same direction from the centre of the nebulosity – to the south – makes us believe that this shift is real.

Observed properties of 3C 48 also give us arguments in favour of that the nuclei is moving in the galaxy. Wampler *et al.* (1975) have obtained a spectrum of the nebulosity to the north from the quasar. The redshift of the nebulosity appears to be larger than that of the quasar – the radial velocity difference is 420 km s^{-1}.

1.3

Another example of an eccentric nucleus situation in a galaxy is demonstrated by the so-called ring galaxies (for the reviews of observational data – see Theys and Spiegel, 1976; or Vorontsov-Vel'yaminov, 1976). The main body of the galaxy has a ring form: the ring can be both narrow and wide. Its diameter is 10–50 kpc, its stellar population is like that of irregulars of Magellanic Clouds type (a lot of young stars and of ionized gas) as its photometry indicates. Inside the ring there is no luminous matter except on the plates made with long exposure one can note weak spiral arms. Finally, these galaxies sometimes have nuclei – though not pointlike as QSO but elliptical, with dimensions $\sim 20\%$ of ring diameter – and absorption lines of their spectra tell about presence of normal stars in these nuclei. The nuclei are sometimes located inside the rings – but not in the centre and not in the focus of the ellipse – sometimes exactly on the rings, and sometimes outside the rings – such nuclei are usually classified as dwarf elliptical companions of ring galaxies without nuclei. Considering these types of ring galaxies one can suspect that they follow a single evolutionary sequence: almost all the material of a disk galaxy was concentrated into the ring by a differential radial flow, and the nuclei was forced to leave the galaxy by some unknown mechanism. Different stages of its motion may produce different types of ring galaxies. In order to explain such transformation, several mechanisms were proposed: galaxy colliding with intergalactic H I cloud or with other galaxy would be transformed in such a way. But Dostal and Metlov (1979) have shown that the probability of such events is too small to give a sufficient number of ring galaxies. Above all, ring galaxies do not concentrate in clusters where the collision probability is higher. The cause which makes the nuclei leave the ring galaxies seems to be internal.

1.4

The well-studied peculiar galaxy NGC 1275 exhibits many extraordinary properties. Pronik (1979) determined a position and a radial velocity of the centre of gas filaments. He found that there were two such centres: their radial velocities are very different ($\Delta v_r = 140$ km s^{-1}) and their positions may be different too – the shift $1''$–$2''$ in the north–south direction is suspected. Pronik (1979) suggests two possible explanations:

either one nucleus having different radial velocities in different moments had two explosions (though the birthtimes of two gas filament systems coincide with each other within the uncertainty 10^7 yr) or there are two exploding nuclei with different radial velocities in the galaxy. Pronik himself prefers the latter explanation; recently the paper of Metik and Pronik (1984) appeared in which a suggestion of two nuclei with the separation $1''$–$2''$ in the north–south direction has been confirmed by new observed data. They have resolved two components of the NGC 1275 nucleus on a plate. These components are situated almost exactly along the north–south axis and have separation $1''.50 \pm 0''.06$ (500 ± 20 pc). Both the components are variable: for 20 min they have changed their blue flux by a factor of 2.5–3 (4–5 σ). Metik and Pronik (1984) relate the binarism of the NGC 1275 nucleus observed by them as with Pronik's (1979) results as with the known emission lines division in the spectrum of the nucleus: its $\Delta\lambda$ implies a radial velocity difference 600 km s^{-1} (Dibaj, 1969). Here we must point out that if the results of all three works are applied to the same binary system then the low limit of the component mass is $2 \times 10^9 M_\odot$ ($\Delta v_r = 140$ km s^{-1}) or even $8 \times 10^9 M_\odot$ ($\Delta v_r = 600$ km s^{-1}). But there exists an alternative model of a binary system explaining emission lines division in the NGC 1275 nucleus spectrum (see Shklovskii, 1978). Radio-interferometric observations (cf. Matveenko *et al.*, 1980) show a two-component structure of the central radio source but these two components are situated along the east–west axis with the separation 1 pc. For such a binary system the lower limit of the component mass is $10^8 M_\odot$ – a much more reasonable estimate. But then the question of two gas filaments centres remains to be unanswered.

1.5

Finally, there are some interesting appearances in the centre of our Galaxy which demonstrates a weak nuclear activity though it has not a Seyfert-like nucleus. Recently, a note by Ozernoy (1984) has been published which proposes an explanation for observations revealed the position difference between the point radio source Sgr A and the infrared object situated in the peak of the stellar density. Moreover, he remarked that a single model cannot explain the galaxy nucleus radiation in all the spectral regions. Ozernoy suggests such a model for the centre of our Galaxy: there are two radiative objects – a superstar with the mass $\sim 10^6 M_\odot$ and a black hole with the mass $\lesssim 4 \times 10^3 M_\odot$ which accretes the stellar wind of the superstar. Their separation seems to be large enough for these two objects being not gravitationally associated: their association energy is smaller than kinetic energy of a single star in the centre of the galaxy. It seems natural to suggest that some time ago these two objects were a binary system which has been disrupted after collapse of the black hole. The black hole having smaller mass than the superstar has received a considerable impulse and has left its place in the centre of the galaxy. So it is now typical 'nomadic' nucleus.

What are theoretical possibilities for a nucleus of a galaxy to become 'nomadic'?

2.1

Shklovskii (1970) has pointed out that active nuclei of galaxies can attain a large proper velocity because of anisotropic generation of relativistic particles. One can suggest that anisotropic collapse would result in the same way. Consider such a collapse. Energy released by the collapse is $E = \alpha Mc^2$ (M is a mass of the resulting black hole, c is the light velocity). If the explosion is not fully isotropic the black hole will attain kinetic energy $E_K = \beta E$, or

$$\frac{Mv^2}{2} = \alpha\beta Mc^2 . \tag{1}$$

The proper velocity of the black hole is given by

$$v = \sqrt{2\alpha\beta}\, c . \tag{2}$$

Assuming that $\sqrt{2\alpha} = 1$ we shall not be too far off. But it is difficult to estimate a coefficient β. However, even if $\beta \gtrsim 10^{-6}$ the black-hole proper velocity is $\gtrsim 300$ km s^{-1}, which is larger than typical stellar velocities in galaxies. Thus it is important to consider consequences of the black-hole motion. Moreover, even if $\beta \gtrsim 10^{-8}$ the effect becomes important for the black holes in globular clusters.

2.2. The Main Processes

In this section we shall consider the main physical processes which determine the fate of the black hole having attained a considerable impulse at the moment of the collapse.

(a) THE GRAVITATIONAL CAPTURE

Suppose that a massive body of plasma collapsed in the centre of a galaxy. If the collapse was accompanied by the ejection of material with the anisotropy coefficient β, the black hole has attained a velocity $v = \sqrt{\beta}\, c$. According to observational evidences stellar density in the centre of galaxy is about 10^6–$10^7\, M_\odot$ pc^{-3}. So we may expect that the black hole leaving the centre will capture all stars closer to the centre than $R_c = 2GM/v^2$. Total mass of the captured stars will be

$$M_c = 4\pi \int_0^{R_c} \rho_* r^2\, \mathrm{d}r = \frac{32}{3}\, \pi\, \frac{G^3 M^3}{v^6}\, \bar{\rho}_* , \tag{3}$$

where ρ_* is the stellar density, r is the distance from the centre, $\bar{\rho}_*$ is the mean stellar density. Or in the dimensionless form,

$$M_c = 3 \times 10^6\, M_8^3 v_8^{-6} \bar{\rho}_6 \tag{4}$$

in $M_\odot$ ($M_8 = M/10^8\, M_\odot$, $v_8 = v/10^8$ cm s^{-1}, $\bar{\rho}_6 = \bar{\rho}_*/10^6\, M_\odot$ pc^{-3}).

Thus the halo of captured stars can be massive enough, and even more massive than the black hole itself. The latter takes place if $\sqrt{\rho_6}\, M_8 v_8^{-3} \gtrsim 7$. As a parabolic velocity is smaller than 10^8 cm s^{-1} for the majority of galaxies, we may see that if the black hole does not leave the galaxy it always would be surrounded by a massive stellar cluster.

(b) THE ACCRETION

As we have seen just above the gravitational interaction of the moving black hole with stars surrounding it leads to the stellar halo formation. This halo is quite similar to the central stellar cluster in the galaxy. So accretion rate defined by stars disruption remains constant as if the black hole has not left the centre of the galaxy. And so we may expect that the energy generated by the accretion on the moving black hole would be close to the luminosity of the brightest active galactic nuclei: $\sim 10^{46}$–10^{48} erg s^{-1}.

If the massive black hole has left the centre without considerable capture of stars then its luminosity is defined by the accretion of galactic gas and by the accretion of galactic background stars. Let us show that galactic gas can provide the main contribution to the accreted material.

The accretion rate of non-interacting particles (stars) is defined by the following expression (cf. Zel'dovich and Novikov, 1967)

$$\dot{M}_* = \pi R_G^2 (u/v)^2 \rho_* v\,, \tag{5}$$

where R_G is the capture radius, $u = (2GM/R_G)^{1/2}$. It is natural to assume the capture radius to be equal to the Roche radius: $R_G = (M/m_*)^{1/3} R_*$ where m_* and R_* are the mass and the radius of stars. Now we have

$$\dot{M}_* = \pi R_* R_G (M/m_*)^{1/3} \rho_* v\,. \tag{6}$$

Gas accretion rate is defined by a standard Hoyle–Lyttleton formula

$$\dot{M}_g = \pi R_G^2 \rho_g v\,, \tag{7}$$

where ρ_g is the interstellar gas density. As a first approximation we assume the black-hole velocity to be much larger than the velocity dispersions of stars and gas clouds. Then the relative contribution of stars to the accretion rate will be given by

$$\frac{\dot{M}_*}{\dot{M}_g} = \frac{R_*}{R_G} (M/m_*)^{1/3} \frac{\rho_*}{\rho_g}\,. \tag{8}$$

Assuming that $R_* \approx 10^{11}$ cm, $m_* = 1\, M_\odot$, we obtain

$$\frac{\dot{M}_*}{\dot{M}_g} = 2 \times 10^{-5} \frac{\rho_*}{\rho_g} M_8^{-2/3} v_8^2\,.$$

This means that for the massive black holes moving inside the galaxy the accretion rate is mostly defined by gas. Consequently, the black-hole luminosity will be given by

$$L \approx \varepsilon \times 10^{43} M_8^2 v_{300}^{-3} \rho_{-24}\ \mathrm{erg\ s^{-1}}\,, \tag{9}$$

where ε is the effectivity of energy generation, $v_{300} = v/300\ \mathrm{km\ s^{-1}}$, $\rho_{-24} = \rho_g/10^{-24}\ \mathrm{g\ cm^{-3}}$. At the presence of magnetic field in accreting gas ε may achieve 20–30% (Shvartsmann, 1971).

(c) THE DYNAMICAL FRICTION

Moving among galactic background stars, the black hole is affected by the deceleration force of dynamical friction. The force of dynamical friction is defined by the expression (cf. Chandrasekhar, 1943)

$$\mathbf{F} = -\frac{4\pi G^2 M^2 \rho_*}{u^3}\,\mathbf{u}\Lambda\,, \tag{10}$$

where $\mathbf{u}$ is the black-hole velocity with respect to the stellar background, Λ is the dimensionless coefficient defined by parameters of stellar velocity distribution and weakly depended on R_G.

Assuming $\mathbf{u} = \mathbf{v}$ we shall obtain the characteristic time of kinetic energy relaxation

$$\tau_{\mathrm{rel}} \approx \frac{E}{\mathbf{F}\cdot\mathbf{v}} = \frac{v^3}{8\pi G^2 M \rho_*}\,\Lambda\,, \tag{11}$$

or, in dimensionless units

$$\tau_{\mathrm{rel}} = 10^{12}\,\Lambda v_8^3 M_8^{-1} \rho_{-24}^{-1}\ \mathrm{yr}\,. \tag{12}$$

2.3. The Fate of the Black Hole Ejected from the Centre

The fate of the black hole strongly depends on the relation between the proper velocity of the black hole v and the parabolic velocity in the galaxy v_p. The parabolic velocity is 500–1000 km s^{-1} for the majority of galaxies. If the proper velocity of the black hole $v \ll v_p$ then according to (12) it will loose its velocity soon enough (for 10^3–10^4 yr) and will fall into the centre of the galaxy.

Let us consider the second case when the velocity of the black hole is large enough but still smaller than parabolic. The black hole will follow an eccentric orbit with a period $\sim 10^8$ yr. If the black hole has a massive stellar halo captured in the galactic centre then such the galaxy will look as a normal galaxy with an active region situated non-centrally. We may expect that the massive halo would be disrupted soon enough by the tidal interaction with galactic stars, particularly during the black hole passage through the galactic centre. Having lost its halo the black hole becomes a very low-luminosity source. In spiral galaxies the source will be periodically flashed up during the passage through the galactic gaseous disk (a sort of transient sources). In this case the luminosity maximum will be defined by the expression (9). If the black-hole mass is very large it is necessary to take into account the influence of its gravitational field on the stellar distribution in the galaxy. The morphology of the galaxy may be strongly distorted and we shall consider the galaxy as an interacting one.

The third case – $v > v_p$ – differs essentially from the two others. In this case the black hole leaves the galaxy. If the total mass of captured stars is not large, then the black-hole luminosity produced by intergalactic gas accretion will be 10^{37}–10^{38} erg s^{-1}. If the black hole has a massive stellar halo then as it has been noted previously, its luminosity can be as high as 10^{46}–10^{48} erg s^{-1}. Such a source, an isolated source without any galaxy around it, has a single possible direction of evolution – a slow depletion. The halo mass cannot be much larger than the black-hole mass, otherwise the black hole would not leave the galaxy. The characteristic lifetime of the black hole at the active state will be, thus

$$\tau_l \approx 2 \times 10^9 \, L_{46}^{-1} M_8 \text{ yr} . \tag{13}$$

Thus we predict an existence of luminous point sources like QSOs but having no host galaxies.

2.4. The Binary Nature of Galactic Nuclei

That galactic nuclei may be binary was pointed out by Komberg (1967) and Shklovskii (1978). Binary nature of galactic nuclei gives additional possibilities for black holes to escape away from the centre of galaxies. In fact, if one of the magnetoids has collapsed and has lost a considerable fraction of its mass, the binary system is disrupted and one of the components obtains a considerable velocity. Note that similar mechanism was proposed to explain runaway stars (Blaauw, 1961). If the masses of both the components are approximately equal then the velocity attained by the black hole after the disruption of the binary system will be close to the orbital one. Let us estimate the largest velocity that can be attained by the black hole after the disruption of the binary. If the orbital velocity of a supermassive binary system is too large, then emission of gravitational waves will result in a rapid dissipation of kinetic energy earlier than the components evolution will finish at the stage of collapse. The characteristic time of binary dissipation by the emission of gravitational waves is defined by the expression (cf. Zel'dovich and Novikov, 1967)

$$t_{\text{gr}} = \frac{5}{16} \frac{GM}{c^3} \left(\frac{r}{R_g} \right)^4 , \tag{14}$$

where r is the distance between the components, R_g is the gravitational radius of the components. Here we assume the components to be equal.

To be disrupted after the collapse it is necessary for the binary that the dissipation time t_{gr} should be larger than the evolution time up to the collapse t_{ev}. This condition puts an upper limit on the orbital velocity and, therefore, on the proper velocity of the components after the collapse. The largest proper velocity of the components appears to be $v_{\max} = 1000$–3000 km s^{-1} in the extended ranges of evolution time and of component mass. That means that in case of the binary system disruption the components can leave the galaxy with all the consequences described above.

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