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EMISSION NUCLEI IN GALAXIES

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ABSTRACT

Some galaxies which show wide emission lines in the spectra of their nuclei are discussed. It is shown that, on statistical grounds, the nuclear emission must last for several times 10^8 years at least. The nuclei are extremely narrow, of the order of 100 parsecs, and, if a normal mass-to-light ratio applies, extremely massive. The width of the emission lines, which indicates velocities of a few thousand kilometers per second, is probably due to fast motions, circular or random, in the gravitational fields of the nuclei. The high star density in the nuclei may provide a source of excitation. In the nucleus of our own Galaxy the radio source Sagittarius gives evidence of strong magnetic fields and large amounts of relativistic particles. A mass of a few times 10^8 solar masses is needed to prevent disintegration of the source. The Andromeda Nebula has a nucleus with a somewhat smaller mass. The occurrence of dense nuclei may be a common characteristic of many galaxies.

INTRODUCTION

In the spectra of a large number of galaxies one or more emission lines are present. Most frequently, only the [O II] λ 3727 doublet and the Hα line are observed. In many spirals, especially in the later types, this emission originates all through the galaxies and is easily explained by the presence of low-density gas and hot stars in these systems. The [O II] emission is also found in a number of ellipticals, where the gas may frequently be in a state of rapid rotation (Osterbrock 1957).

In some, rather rare, galaxies a much richer emission spectrum is found, which originates in the nucleus. Eleven such systems have been listed by Seyfert (1943), who studied some of them in detail (NGC 1275 does not belong to this group, according to Minkowski 1957). We may define the membership of this group by the following criteria: (1) the nuclei are extremely bright and condensed, with diameters of the order of 100 parsecs; (2) the absorption lines in the spectra of the nuclei, if present at all, are wide and diffuse; (3) the emission lines are wide, indicating velocities up to a few thousand kilometers per second (in most cases the hydrogen lines are much wider than the other emission lines); and (4) the emission spectrum is characterized by a high excitation (in some cases [Fe VII] [I.P. = 102 volts] is observed).

Nine Sa and Sb galaxies of this type brighter than $m_{pg} = 13.0$ are known, seven of which are in the northern hemisphere. This indicates that at least 4 per cent of the Sa and Sb galaxies have such nuclei. Thus the time during which a galaxy is characterized by such nuclear emission must be of the order of a few times 10^8 years if this is a normal evolutionary stage for all Sa and Sb galaxies. If nuclear emission occurs only in special galaxies, the time scale must be longer.

Morgan (1958) has classified seven of the nuclear emission spirals. Out of somewhat over sixty of such galaxies in the whole catalogue of Morgan, five are definitely or probably of type gS. It thus seems that, as the classification becomes more refined, the galaxies with emission nuclei make up an increasingly large fraction of a definite class of galaxies.

If we suppose that the observed velocities indicate that the gas moves out of the nucleus (Burbidge 1958), the emission would last for only 10^5 years, unless a sufficiently large supply of new gas were available. Such a supply cannot be derived from gas presently in the nucleus. Thus either the measured velocities do not indicate an expansion and

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the gas remains in the nucleus, or there is a strong large-scale circulation in these system. We shall show in the following sections that the first interpretation seems the more likely.

PHYSICAL CONDITIONS IN THE EMISSION NUCLEI

The observational data on the nearest galaxies observed by Seyfert (1943) are given in Table 1. In the successive rows are shown the apparent photographic magnitudes of the galaxies (Humason *et al.* 1956) and of the nuclei (Seyfert), the red shifts (Humason *et al.*), the distances computed from a Hubble constant of 75 km/sec/Mpc (Sandage 1958), the galactic latitude and the interstellar absorption (Abs. = $0^{m}.25$ cosec b), and the absolute photographic magnitudes of these galaxies and of their nuclei. In the next

TABLE 1

CHARACTERISTICS OF SOME GALAXIES WITH NUCLEAR EMISSION

	NGC 1068	NGC 4051	NGC 4151
m_{pg}	9.9	11.0	11.2
$^{*}m_{pg}$	13.0	14.0	12.0
V_r (km/sec)	1082	679	979
D (Mpc)	14.4	9.1	13.1
b	$-51°$	$+71°$	$+76°$
Abs.	0.32	0.26	0.26
M_{pg}	-21.2	-19.0	-19.6
$^{*}M_{pg}$	-18.1	-16.0	-18.8
R (app.)	1″	1″.8	1″.2
R (pc)	70	79	76
$V_{0.1}$ (km/sec)	± 1500	± 950	± 3000
$H\beta$ (erg/sec)	5.9×10^{40}	...	1.2×10^{41} (core) 3.7×10^{41} (wing)
T_e	20000°	(100000°)	39000° (core) (10000°) (wing)
M_{max} ($m_{\odot}$)	9×10^{6}	...	3×10^{7}
$N_{e\,min}$ (cm^{-3})	200	...	500
M_{min} ($m_{\odot}$)	1×10^{5}	...	9×10^{5}
$N_{e\,max}$ (cm^{-3})	1.6×10^{4}	...	1.6×10^{4}
E_k (erg)	5×10^{55}–5×10^{53}	...	2×10^{57}–5×10^{55}
M_{nuc} ($m_{\odot}$)	6×10^{10}	9×10^{9}	1.2×10^{11}
Θ_c (km/sec)	1900	700	2600

two rows upper limits in seconds of arc and in parsecs are given for the radii of the nuclei. We estimated these from microphotometer tracings of short-exposure plates taken with the 100-inch telescope at Mount Wilson by Baade (NGC 1068, NGC 4051) and Hubble (NGC 4151). In the next rows follow the width of the hydrogen lines at the point where the intensity is one-tenth the intensity at the line center and the intensity of $H\beta$, roughly estimated from Seyfert's data. The data are not very precise, but, in view of the uncertainties in the calibration of Seyfert's spectra, a more detailed evaluation would have no significance.

From the intensity ratio of the [O III] lines, given by Seyfert, electron temperatures in the gas were derived. This procedure does not give information on the gas which emits the wide wings of the hydrogen lines. The interpretation of these wings is uncertain; we shall tentatively assume that they are produced in gas with a fairly low temperature—which reduces the intensity of the forbidden lines—exposed to less high-frequency radiation than the gas which emits the cores of the lines. This last requirement is needed to reduce the ionization and thereby the intensity of the [O III] lines and the helium lines. These two assumptions are to a certain extent interrelated, since a steep spectrum beyond the Lyman limit will generally reduce the electron temperature. This discussion implicitly assumes that the excitation is not collisional. If the excitation were primarily collisional, it is difficult to see how the hydrogen lines could be strongly excited, without a corresponding excitation of some forbidden line. More or less arbitrarily we shall assume $T_e = 10000°$ for the gas which emits the hydrogen wings in NGC 4151.

If we assume that the gas fills the volume of the nuclei uniformly, we can immediately compute the mass of the gas from the intensity of Hβ and the electron temperature. These masses are evidently maximum values, since inhomogeneities in the gas enhance the emission. A minimum estimate for the mass may be obtained as follows. Seyfert has measured both the red and violet [S II] lines. For a known electron temperature their intensity ratio determines the density. However, their measured intensity ratio depends on the calibration over a wide interval in the spectrum, which is quite uncertain. In the spectrum Hα lies close to the red sulfur lines and Hδ close to the violet sulfur lines. Thus, if we assume the Balmer decrement known, the calibration difficulty may be eliminated. Assuming a radiative decrement, we obtain from the sulfur lines an electron density of about 1.6×10^4 cm^{-3} for both NGC 1068 and NGC 4151. Both the maximum and the minimum masses and the corresponding densities are given in Table 1. If the Balmer decrement were collisional, the ratio of the intensities of the red and violet [S II] lines would have to be increased. This would decrease the electron densities, but, since the b_n values for the hydrogen lines would be larger, the minimum mass would not change very much. The maximum masses would be somewhat less than half the values in the table in this case. It should be noted that all masses given refer to ionized matter. An unknown amount of neutral hydrogen might be present in the outer regions of the nuclei. The total kinetic energies given in Table 1 were derived from the masses and the profiles of the hydrogen lines.

Nothing is known about the stellar population of the nuclei. To obtain an estimate of their mass, we shall assume that the luminosity of the nuclei is due to the contributions from individual stars and that the mass-luminosity ratio is 25, as it is, on the average, in galaxies of early spiral type. The masses of the nuclei, given in Table 1, appear to be very large. From the masses and the radii of the nuclei the circular velocities at their surface were computed. It is striking to note the order-of-magnitude agreement between the values of Θ_c and the velocities observed in the hydrogen lines. Thus, if our assumptions on the nature of the continuous spectrum of the nuclei are correct, the high gas velocities are a direct consequence of a strong gravitational field, and most of the gas need not escape from the nucleus. The very high stellar densities in the nuclei may give an adequate explanation for the excitation of the gas if a sufficient number of blue population II stars or similar objects are present.

Since most of these emission nuclei are found in spirals, we may suppose that the velocities are primarily rotational, although large random motions may also be present. If this is so, we may consider a model in which the stellar density is highest near the center. Then the ionizing radiation is strongest near the center, where the velocities are comparatively low. In this part the line cores could be formed. In the more outlying regions the velocities would be higher, the ionizing radiation more degraded, and the temperature of the gas therefore lower; thus the hydrogen wings might be formed there.

The velocity dispersion of the stars in the nuclei will be about the same as that of the gas. Thus the absorption lines in the nuclei should be broad and weak if the most luminous stars have the same space distribution as the gas. If the luminous stars were strongly concentrated toward the center, this would not necessarily be true. Seyfert states that in NGC 1068 the K line is not very wide. Some caution is needed in judging this result because the nucleus of this galaxy is surrounded by a fairly bright ringlike structure, which on small-scale spectra might influence the spectrum of the nucleus. In

NGC 7469, however, the K line is extremely shallow and at least 50 A wide, according to Seyfert.

Before proceeding with the discussion of these nuclei, we shall consider the nucleus of our own Galaxy, which, on a very different scale, may show some similarities to these emission nuclei.

THE NUCLEUS OF OUR GALAXY

The radio source Sagittarius A is presumably located at the center of our Galaxy. This object is the only source of direct evidence for the presence of gas and magnetic fields in the galactic nucleus. According to Westerhout (1958), it consists of a thermal source, superimposed on which is a somewhat wider non-thermal source. The thermal source is due to a mass of ionized hydrogen of 2.5×10^5 solar masses in an ellipsoidal volume with semiaxes of 20 and 40 parsecs. Presumably centered on this mass is the non-thermal source with semiaxes of 75 and 150 parsecs. The spectral index of the non-thermal spectrum is probably near 0.7. From Westerhout's data we find that the emission from the non-thermal source is

$$J(\nu) = 1.9 \times 10^{26} \left(\frac{\nu}{1.39 \times 10^9}\right)^{-0.7} \text{erg sec}^{-1}\,(\text{c/s})^{-1}. \tag{1}$$

If the emission is synchrotron radiation from electrons with an energy distribution

$$n(E)\,dE = kE^{-2.4}dE\,, \tag{2}$$

the total emission is given by the expression

$$J(\nu) = 1.17 \times 10^{-22}\,(1.61 \times 10^{13})^{0.7} k\nu^{-0.7} H_{\perp}^{1.7} \int_0^{\infty} a^{-0.3} F(a)\,da\,. \tag{3}$$

The function $F(a)$ has been tabulated by Oort and Walraven (1956). Assuming that, on the average, $H_{\perp} = \pi/4\, H$, we obtain, from equations (1) and (3),

$$kH^{1.7} = 2.0 \times 10^{45}\,. \tag{4}$$

The energy of the electrons is given by

$$\mathcal{E}_e = \tfrac{5}{2}\,(E_{\min}^{-0.4} - E_{\max}^{-0.4})\ \text{Bev}\,, \tag{5}$$

where $E_{\min}$ and $E_{\max}$ define the interval in which equation (2) is valid. Since the spectrum extends at least over several hundreds of megacycles, we have $E_{\max} \gg E_{\min}$; therefore, we may take $E_{\max} = \infty$ in equation (5) without an appreciable error. The critical frequency corresponding to $E_{\min}$ must be of the order of 10 Mc/s (or less). Therefore, we have

$$E_{\min}^2 = 7.9 \times 10^{-7} H^{-1}\ \text{Bev}\,. \tag{6}$$

After eliminating k, we obtain

$$\mathcal{E}_e = 1.3 \times 10^{44} H^{-1.5}\ \text{erg}\,. \tag{7}$$

If the critical frequency were assumed to be a factor of 10 lower, $\mathcal{E}_e$ would be increased by only a factor of 1.6. It is very improbable that only relativistic electrons are present. In the spiral arms the total energy of all cosmic-ray particles may be estimated to be of the order of a factor of 100 larger than the energy of the relativistic electrons. Adopting the same figure for the galactic nucleus, we have

$$\mathcal{E}_{ep} = 1.3 \times 10^{46} H^{-1.5}\ \text{erg}\,. \tag{8}$$

The magnetic energy in the nucleus is

$$\mathfrak{M} = 8.3 \times 10^{60} H^2 \text{ ergs} . \tag{9}$$

The minimum of the total energy is reached if

$$H = 5.4 \times 10^{-5} \text{ oersted} ; \qquad \mathfrak{M} = 2.4 \times 10^{52} \text{ ergs} ; \qquad \mathcal{E}_{ep} = 3.3 \times 10^{52} \text{ ergs} . \tag{10}$$

To maintain such a high cosmic-ray density in the nucleus, the magnetic field must be closed, for if the particles escaped freely, an impossibly high acceleration rate would be needed. This argument would not apply if the particle density were much lower than indicated by equation (10). We might then think that the source at the galactic nucleus would be due only to a strong magnetic field, the abundance of relativistic electrons being the same as in other parts of the Galaxy. However, for this to be possible, the field strength would have to be about 7×10^{-4} oersted, and we shall show below that such a field cannot be contained in the nucleus for dynamical reasons.

The pressure of the magnetic field and the cosmic-ray particles tend to disrupt the source. To keep it together for several millions of years, a compensating force is needed. Pressures from outside the source are relatively unimportant. The gas pressure is negligible, and magnetic pressures outside the nucleus are also comparatively small, since Mills's (1958) observations show that the general magnetic field in the Galaxy does not increase very strongly toward the center. Thus the only force is internal gravitation. The gravitational forces can keep the ionized gas together, and, since the lines of force are partially imbedded in the ionized gas, the gas may keep the field in the source. To estimate the total mass needed in the galactic nucleus, we apply the virial theorem (Chandrasekhar and Fermi 1953). This gives us

$$|\Omega| \simeq \frac{G M M_{\text{gas}}}{R} > \mathfrak{M} + 2\mathcal{E}_{ep} = 9 \times 10^{52} \text{ ergs} . \tag{11}$$

With Westerhout's estimate for M_{gas} and $R = 30$ pc, we obtain

$$M > 1.3 \times 10^{8} m_{\odot} . \tag{12}$$

It can be shown that a nucleus with a mass smaller than $10^9\ m_{\odot}$ does not have much observable effect on the stellar dynamics of the galactic system. However, if the field were 7×10^{-4} oersted, corresponding to a field that is not closed, a mass of $8 \times 10^9\ m_{\odot}$ would be required, and this is more than can be reconciled with the estimated rotational velocities in the inner regions of the Galaxy. Since in the above computations we have taken all energies as small as possible and have neglected motions in the gas, the result in equation (12) is evidently an absolute minimum. A value of about 5×10^8 solar masses appears more reasonable.

The degree of ionization seems to be much higher inside the nucleus than outside, although there the density is lower. This indicates that the ionizing radiation is confined mainly to the nucleus. The high stellar densities in the nucleus, implied by a total mass of several times 10^8 solar masses, appear to give a natural explanation of this fact.

THE RADIO EMISSION OF NGC 1068

The radio emission of NGC 1068 is about four times stronger than the normal for Sb galaxies. In view of the large amount of gas in its nucleus, we shall investigate the possibility that a large part of this radiation originates in the nucleus.

Making use of Mills's (1958) data, we obtain, for NGC 1068,

$$J(\nu) = 4.6 \times 10^{30} \text{ erg sec}^{-1} \ (\text{c/s})^{-1} . \tag{13}$$

Performing the same calculation as for the galactic nucleus and assuming that the radiation has a spectral index 0.7 and originates in a volume with radius 70 pc, we obtain, for minimum total energy,

$$H = 8.5 \times 10^{-4} \text{ oersted} ; \quad \mathfrak{M} = 1.2 \times 10^{54} \text{ erg} ; \quad \mathcal{E}_{ep} = 1.6 \times 10^{54} \text{ erg} . \tag{14}$$

Since these energies are of the same order of magnitude as the kinetic energy of the gas motions, the nucleus can contain such a field. This field might have a strong influence on the motions of the gas. This calculation shows that strong radio emission from the nucleus is possible. An accurate determination of the radio diameter of the source is needed to determine whether this is actually the case or whether the radio emission originates mainly in the halo. It should be noted that another nuclear emission galaxy, NGC 4258, has a more normal radio emission. Thus excessive radio emission appears not to be a common characteristic of these objects.

CONCLUDING REMARKS

In the preceding sections we have investigated the physical conditions in the nuclei of some galaxies. The basic assumptions involved are that the continuous spectrum from the emission nuclei is produced by stars and that these nuclei are more or less stationary.

As for the first assumption, it might be thought that the continuum is due to some other mechanism—for example, synchrotron radiation or bremsstrahlung. For both these possibilities the mechanism of radiation contributes to the instability of the nucleus—the first because strong magnetic fields are needed to have synchrotron radiation in the optical part of the spectrum, the second because much gas is needed in some state of high-velocity turbulence. Thus for the nuclei to be stationary, the masses of the nuclei would have to be still larger, and now this mass would have to be largely non-luminous. The fact that the assumption of ordinary stellar light from the nuclei leads directly to the required masses gives rather strong support to the first assumption.

The stationariness of the emission nuclei appears to be indicated by the statistics, although these could be interpreted by the assumption that such nuclei dissipate away but are formed anew from time to time. This seems very improbable; for if such nuclei disintegrate immediately after their formation, it is difficult to see how they could be formed in the first place. We would expect a strong attractive force in the nucleus to be needed for formation, and this brings us back to massive nuclei again. Such a force would also be needed if the motions were part of a large-scale circulation.

According to Baade (1958), the Andromeda Nebula also has a sharp nucleus with semiaxes of about 4 and 2 parsecs. The mass of this nucleus may be estimated to be $5 \times 10^7 \, m_\odot$, for a mass-luminosity ratio of 25.

It thus appears that very condensed nuclei may be a common phenomenon in spiral galaxies, although the nuclei are only rarely as bright and massive as in the galaxies with broad nuclear emission lines.

The ratio of the mass of the ionized gas to the total mass in the nuclei of NGC 1068 and NGC 4151 is about 2×10^{-4} or smaller and, in our own Galaxy, 10^{-3} or less. Since the stars in these nuclei may have lost an appreciable amount of gas during their evolution, some gas may have escaped from the nuclei, but at a low rate.

The relaxation times in the nuclei of the galaxies discussed here are extremely long (10^{14} years for NGC 4151). It is therefore difficult to see how such a nucleus with a very low angular momentum per unit mass could be formed in a stellar system. Presumably, these nuclei had already originated before the protogalaxy condensed into stars.

A final remark may be made on our Galaxy. It is known that in the inner regions of the Galaxy a large amount of hydrogen is in a state of rapid expansion. Since it is inconceivable that sufficient gas is present in the nucleus to maintain this gas flow, the most plausible idea seems to be that these motions are part of some general circulation through the galactic system, gas moving away from the inner regions in the plane of the Galaxy and falling into these regions from the halo. It seems natural to suppose that the flow pattern is determined by magnetic fields. Although we do not intend to discuss this circulation here, we may point out that, since the field in the nucleus was shown above to be closed, such a circulation cannot go through the nucleus proper. Thus the hydrogen motions in the Galaxy and the gas motions in the nuclear emission galaxies are two essentially different and unrelated phenomena. However, the large mass of the nucleus may play a role in stabilizing a regular flow system.

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Note added, April 10, 1959.—In this same issue (p. 26) E. M. Burbidge, G. R. Burbidge, and K. H. Prendergast discuss rotational velocities in NGC 1068, which, unless they are strongly affected by the magnetic fields, which may be present in the interior regions of this galaxy, indicate a very low M over L ratio. Then the mass of the nucleus is too small to prevent the escape of the gas. However, this would not affect our results on the more typical Seyfert galaxies, in which the hydrogen lines are very different from the other emission lines; this would be hard to explain if the gas were streaming out of the nucleus.

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