THEORETICAL CONSIDERATIONS OF COMPACT OBJECTS

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Abstract. The rotation of massive objects with magnetic fields may provide the highly efficient means of energy conversion required to explain the high luminosity of compact objects. Several variations of the 'massive rotator' model are discussed.

The two main difficulties in our understanding of compact objects concern the energy requirement and the radiation mechanism. With regard to the latter various models involving synchrotron and Compton radiation, with cutoff due to self absorption or cyclotron turnover have been discussed. The main difficulty is caused by the sharply peaked strong infrared radiation observed in several objects. Thermal dust models for the infrared are attractive because we know from the intensity ratios of certain emission lines that dust is present in the nuclei of some Seyferts. However, the rapid time variations in the infrared, which were reported here, appear to stretch the dust models beyond the breaking point. If so a non-thermal mechanism is called for and it seems likely that, whatever may be the detailed process, much of the radiation derives from energetic particles.

In Table I we have assembled estimates of the energy requirements and time scales for some representative objects. The values listed are on the conservative side. For example recent results by Kleinmann and Low (1970) may indicate that the far infrared emission of 3C 273 could be as high as 10^{49} erg s^{-1}, while the results reported here by Dr Neugebauer show that some QSOs emit at least 10^{48} erg s^{-1} already in the more accessible parts of the infrared. The time-scales are quite uncertain. In the case of 3C 273 all we have is the light travel time to the tip of the jet, while for the Seyferts the fact that 1% of the brighter galaxies belong to this class only establishes a minimum total duration (not necessarily continuous) of 10^8 yr. Inspecting the table we see that energy yields of $10^6\ M_\odot\ c^2$ – partly in the form of relativistic electrons are required

TABLE I

Luminosity L, time-scales and energy requirements E for some objects

	L (erg s^{-1})	(yr)	E (erg)
3C 273	10^{47}	$10^{5.5}$	10^{60}
NGC 1068	$10^{46.5}$	10^{8}	10^{62}
Cyg A	$10^{44.5}$		(10^{60})[a]

[a] equipartition energy for electrons.

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for radio galaxies and QSOs, while for the Seyferts the long term yield is no less than $10^8\ M_\odot\ c^2$. While the figures in Table I represent modest estimates for the more energetic objects it should be kept in mind that the luminosity functions of QSOs and radio galaxies are quite steep. For example for the optical radiation of the QSOs Schmidt (1970) finds a luminosity function $n(L) \propto L^{-2.2}$. Either the formation rate of the fainter objects is much larger than that for bright ones or the fainter objects live much longer.

The time variations impose severe constraints on the spatial extent of the objects. Although counter examples can be constructed, it seems unlikely that the emission comes from regions with linear dimensions *much* larger than the velocity of light multiplied by the characteristic time. Both in the QSOs and in NGC 1068 time scales of the order of a day appear to be involved, indicating emission regions no more than 10^{16} cm across. Direct interferometric observation of a radio component in M87 with a diameter less than 10^{17} cm appears to confirm these very small sizes. Probably the region in which the energy is primarily released is even smaller. The presently available data do not yet allow one to conclude that the same emission region is responsible for all variations, but the very fragmentary polarization data which tend to show some reproducibility perhaps suggest that this is the case.

Not much is known about the total mass available in the inner nuclei of galaxies, but some useful upper limits exist. In NGC 1068 Burbidge *et al.* (1959) obtained an upper limit of $3 \times 10^9\ M_\odot$. From Dr King's remarks here it would seem that the limits in some giant ellipticals are of the same order, while the rotation curve for our own galaxy seems to be incompatible with the presence of a central mass much in excess of $1 \times 10^9\ M_\odot$.

Comparing the available mass with the total energy release in NGC 1068 we conclude that a conversion efficiency of several percent of Mc^2 seems to be achieved. At least in the radio galaxies much of the energy seems to go into relativistic electrons. Inspecting the older mechanisms we are extremely doubtful that a Fermi-mechanism, supernova-shell expansion or star collisions could have the required efficiency, particularly for the electrons.

In the case of the Crab Nebula pulsar we have an object of very small size which converts rotational energy with very high efficiency (20% or so) into energy of relativistic electrons, presumably through the effect of a strong magnetic field in the pulsar. It seems tempting to scale the Crab Nebula mechanism to objects of much greater mass. Investigations of massive rotating objects with magnetic fields have recently been made by several investigators (Morrison, 1969; Cavaliere *et al.*, 1969; Woltjer, 1970; Fowler, 1970; and with somewhat different emphasis by Ozernoy, 1969; and Piddington, 1970; also Lynden-Bell, 1969). Closely related objects were discussed earlier by Hoyle and Fowler (1963) who referred to these objects as supermassive stars, spinars, magnetoids or massive rotators. A rough outline of the contents of some of these investigations follows.

Suppose we have a non-relativistic cold object which is supported mainly centrifugally (angular velocity Ω) and which has a magnetic field B. We treat the object as if it were a sphere of uniform density with radius R. From the virial theorem we find that mechanical equilibrium requires that

$$\Omega^2 R^3 = 3GM/5$$

If we assume that the electromagnetic stresses take away angular momentum, J, in the same way as it is thought to occur in pulsars (Pacini, 1967; Ostriker and Gunn, 1969; Goldreich and Julian, 1969) we have an expression of the following form

$$\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{2}{5} M \frac{\mathrm{d}(R^2\Omega)}{\mathrm{d}t} = -\text{ const } \Omega^3 R^6 B^2 .$$

If magnetic flux, Φ, is conserved during the evolution of the body we have

$$\Phi = BR^2 = \text{const}$$

and combining these expressions

$$\Omega = \frac{\Omega_0}{(1 - t/\tau_0)^{1/2}}, \qquad \tau_0 = \text{const}\,\frac{M}{\Phi^2 \Omega_0^2},$$

with Ω_0 referring to $t=0$. If we assume that the energy is ultimately converted into particles and radiated with an efficiency s we obtain for the luminosity L:

$$L \propto s\Phi^2\Omega^4 = \frac{L_0}{(1 - t/\tau_0)^{4/3}}$$

with $L = L_0$ at $t=0$. We note that in case of a steady state population this luminosity law corresponds to a steep luminosity function, $n(L) \sim L^{-7/4}$, even if all objects have the same value of M and Φ.

In order to fix the values of M and Φ some assumptions have to be made. Morrison assumes that the 200 day period of 3C 345 can be identified with the rotation period while Cavaliere *et al.* let Φ correspond to that in a typical region of the interstellar medium. Fowler (whose object is not cold but an $n=3$ polytrope) also obtains Ω from the 200 day period but interprets the additional 50 day time scale as a pulsation period. These approaches lead to values of $M \approx 10^9\ M_\odot$. We ourselves have considered it unlikely that the evolution terminates before R is of the order of the Schwarzschild radius R_{sch} and therefore take the most luminous objects to have $R \approx R_{\mathrm{sch}}$. Somewhat smaller masses ($10^8\ M_\odot$), radii of $10^{13} - 10^{14}$ cm and values of B near 10^6 G are obtained, corresponding to rotation periods near 10^4 sec. We then interpret the bursts with a time scale of 200 days as perhaps more similar to the 'wisps' in the Crab Nebula. Clearly in these discussions a better knowledge of the fastest time variations in QSOs would be most useful. The very active and luminous QSOs may well be in their later evolutionary phases and the activity for detecting rotation related regularities would present itself in the more stable objects without major fluctuations. At the same time the amplitudes of the more regular variations may be quite small. Again the case of the Crab Nebula is instructive, the pulsar related variations in the integrated light being only of the order of 1%. Because in the massive rotators differential rotation may be expected to occur the situation might be even less favorable.

The above discussion of the massive rotators is quite primitive. In some phases the objects may well be hot – supported partly by radiation pressure – as a consequence of nuclear processes and a substantial amount of light could be thermal (Hoyle and Fowler, 1963). If the objects are cold they are likely to be more in the shape of thin disks – like those studied relativistically by Salpeter and Wagoner. In that case instabilities probably will result in fragmentation. If the fragments are very small the disk might look more like a collection of pulsars – as in the model proposed by Rees. If in the inner parts a collapsed object, (black hole), has been formed and if angular momentum from infalling gas is transported out magnetohydrodynamically the situation would be that envisaged by Lynden-Bell with a steady flow into the black hole. And finally even if the rotators are formed they are unlikely to be of uniform density and differential rotation is expected. As a result the poloidal magnetic fields would be twisted up, resulting in much instability as discussed by Morrison and Ozernoy.

The formation of bodies of large mass in the centers of galaxies presents great difficulties. Spitzer (1970) has studied a model where repeated cycles of star formation and stellar mass loss lead to a nucleus of high stellar density. Once such a region is formed, stellar dynamical relaxation and finally star collisions, become important and will result in a large increase of the central density. During the stellar collisions much thermal energy may be radiated. However the effects of angular momentum remain to be fully understood. Direct condensation of intergalactic gas may be an alternative.

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Discussion on Papers by Shklovsky and Woltjer

Arp: I have looked at the distribution of globular clusters around M87 several times and have never noticed any strong relationship to the line of the jet. I would be very disappointed if I had missed such an asymmetry.

The objects which *are* lined up very well with the line of the jet and counterjet are the E galaxies in the neighborhood of M87. These E galaxies have masses which are orders of magnitudes greater than those of the globular clusters which Shklovsky suggests are ejected. The Shklovsky suggestion seems observationally, however, a step in the right direction.

Baum: Some years ago I investigated the distribution of the small bodies, supposedly globular clusters, surrounding M87. My purpose was to compare their radial distribution with the luminosity profile of the main body, but I would have noticed a pronounced asymmetry if it were present, as asserted by Shklovsky. I did not notice any such asymmetry but shall be interested in re-examining my data with this possibility in mind.

Barnothy: You have mentioned Morrison's rotating model as one of the more plausible models of QSOs. I have investigated the efficiency of the synchrotron mechanism which is used in this model to transform the rotational energy into optical radiation and found that its efficiency is lower by a factor 10^{24} than needed. During my correspondence with Dr Morrison he suggested two additional assumptions, but even these would leave a discrepancy by a factor of 10^9.

Woltjer: There appears to be no difficulty in converting rotational energy efficiently into relativistic electron energy. With a suitable magnetic field much of this energy can be converted into infrared and (possibly indirectly by inverse Compton) optical radiation.

Felten: With regard to Shklovsky's idea (remarkable how much response is drawn by a qualitative suggestion which is specific and somewhat individual), one would not expect that most of the relativistic particles would end up in the blobs which represent their recoil. One might think, for example, that they had mostly flown off 10 or 100 times as far in the opposite direction. We should think about where these electrons are and whether they can be observed to test the model. Has Shklovsky discussed this?

Woltjer: No. However it seems to me that the electrons might again be deflected by magnetic fields in the galaxy; if so, the interstellar matter in which these fields are anchored would ultimately absorb the momentum.

Smith: An observational comment may be of interest, regarding your suggestion that 10^4 s should be some kind of lower limit to the time scale of significant brightness variations to be seen in massive core objects. Angione has examined a number of QSOs photo-electrically for rapid variations; the fastest found was 3C 454.3, with changes of 30–40% in times of several hours, although in most cases the changes were of the order of, or less than, a few per cent per day.

Ozernoy: If, firstly, the physical nature of quasars and quasarlike phenomena in galactic nuclei is the same and differs mainly in the scale of energy output from magnetoids and if, secondly, the

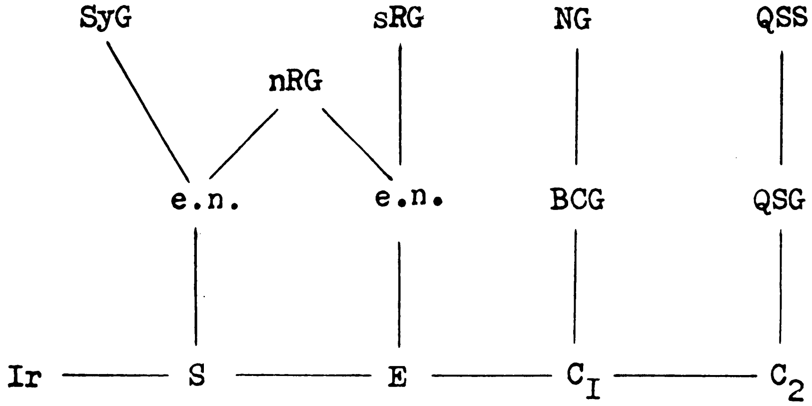

Fig. 1. The extended Hubble sequence of galaxies.

harmonic mean time for the active phase is about 10^8 yr, one can derive theoretically the directions of evolution of different kinds of galaxies. These directions are represented as an extended Hubble sequence of galaxies (see Figure 1).

Here Seyfert galaxies (SyG), strong radio galaxies (sRG), N-galaxies (NG) and quasi-stellar radio-sources (QSS) are regarded as a 'ceiling' of excited states of galaxies of the types spiral (S), elliptical (E) and two kinds of very compact galaxies designated C_1 and C_2 respectively. These galaxies (S, E, C_1 and C_2) are considered as 'ground states' of galaxies.

Blue compact galaxies (BCG) and quasi-stellar galaxies (QSG) are the intermediate excited states' analogous to 'excited nuclei' in normal galaxies, where compact sources of non-thermal radiation exist as described in the paper by Dr Ekers.

The galaxies in the ground state are not connected genetically and differ by initial conditions, that is mainly by the total mass and angular momentum. The vertical lines point out the only possible directions of the excitation of galactic nuclei. For example, the transition of QSS to RG or vice versa is unlikely to be expected. The ground states of QSS and NG are special compact galaxies, and it may be expected that their spatial densities nearly coincide with those for BCG and QSG if a mean harmonic life-time of NG and QSS is about 10^8 yr. If this time is closer to 10^6 yr, these densities are 10^2 greater than those for BCG and QSS.

An excited state of a galaxy should be periodically repeated (with a characteristic interval of about 10^8 yr) during the whole life of a galaxy. The decrement of this process is determined by a gradual change of conditions for a magnetoid reproduction.

Dr Morgan kindly informed me at this Symposium that the theoretical scheme presented (and described in detail in Astronomical Circular of the U.S.S.R. No. 581) is very similar to his classification obtained from an observational point of view.