EMISSION FROM THE NUCLEI OF NEARBY GALAXIES: EVIDENCE FOR MASSIVE BLACK HOLES?

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1. INTRODUCTION

The non-stellar activity in the nuclei of nearby galaxies poses problems of its own. But it gains added interest insofar as it may provide clues to the nature of quasars and the unusually energetic nuclei of some more remote galaxies. The evident qualitative resemblance between these spectacular phenomena and some of the nearby galactic nuclei discussed at this symposium suggests that we may be witnessing a scaled-down or slow-motion version of the same physical mechanism; and the likelihood that dead quasars vastly outnumber living ones suggests that defunct remnants - perhaps displaying some low-level residual activity - may lurk in the centres of most large galaxies.

In this contribution I shall first venture some conjectures on scenarios whereby a massive black hole could form in a galactic nucleus, and the characteristic features of accretion onto it. I shall then suggest how some observed phenomena - particularly the radio and x-ray continuum - can be interpreted in terms of such processes. And in conclusion I shall mention some other tests for (or limits on) massive black holes in nearby galaxies.

Once the star or gas density in a galactic nucleus exceeds some threshold value, well-known arguments suggest that some kind of 'runaway' evolution ensues. This evolution can plausibly lead to the formation of a massive black hole, and the quasar phenomenon can be interpreted as a result of rapid accretion onto such a body. This process seems able to convert rest-mass energy into appropriate non-thermal forms with higher efficiency than any likely precursor stages. The scenarios that terminate in massive black holes are numerous (see Figure 1) and various lower-level manifestations of activity in nuclei may be attributable to the preliminary stages. (e.g. star-gas interactions or multiple supernovae in dense star clusters, supermassive objects or 'magnetoids', etc).

The evolution sketched in Figure 1 suggests that 'dead' quasars - interpreted as massive black holes that are now being starved of fuel-

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outnumber active ones by a factor which, though uncertain, may lie in the range 10^4-10^5. This figure allows for the number of generations of quasars in a Hubble time (10^3-10^2 if the characteristic lifetime is 10^7-10^8 years) and for the evidence that their density per comoving volume was perhaps 10^2-10^3 times higher at the epoch corresponding to $z \doteq 2$ than at the present time. It is thus possible that dead quasars could be as common as large galaxies.

These massive black holes could be detected by their influence on the density distribution or velocity dispersion of the stars around them; or there may be some luminosity arising from slow accretion of stars and gas. This latter process could be the explanation for some of the compact sources observed in some nuclei (though we should of course be open-minded about the possibility that some of the precursor stages shown in Figure 1 might also be relevant).

2. LOW-LEVEL ACCRETION ONTO MASSIVE BLACK HOLES

The masses involved in the production of a quasar or strong radio source are likely to be $\gtrsim 10^7$ solar masses, so it is convenient to introduce the parameter M_7. The Schwarzschild radius is then $r_s \simeq 3.\ 10^{12}\ M_7$ cm. It is interesting to ask whether the limited data are consistent with a model in which the compact continuum emission from nuclei results from accretion onto such objects. The theory of this process, with special application to quasars, has been discussed at length elsewhere (Rees 1977, and references cited therein). The rate of accretion required in the present context is low, in the sense that $\dot{M} \ll \dot{M}_{crit}$. The 'critical' accretion rate $\dot{M}_{crit} \simeq 10^{-2}\ \varepsilon^{-1}\ M_7$ solar masses per year is that needed to generate the Eddington luminosity, assuming an efficiency factor of ε. When $\dot{M} \ll \dot{M}_{crit}$, the densities around the hole are lower than in the 'critical' case, and the cooling timescale tends to be longer than the infall time, unless the temperature gets so high that relativistic cooling processes (pair production, synchrotron and inverse Compton emission, etc) can come into play. This means that the infalling gas will heat up to a very high temperature, and the fraction of radiation emitted non-thermally from near the hole would be higher than for quasars. If there is a magnetic field in the gas, it may be amplified to a value comparable to the equipartition strength, which is approximately

$$B_{eq} \simeq 10^6\ M_7^{-\frac{1}{2}} (\dot{M} / \dot{M}_{crit})^{\frac{1}{2}}\ (r / r_s)^{-5/4} (v_{infall}/v_{free\ fall})^{-\frac{1}{2}}\ \varsigma .$$

For disc-type accretion, v_{infall} may be much less than $v_{free\ fall}$, but when the inflow is 'quasi-spherical' the two would be comparable. When $\dot{M} \ll \dot{M}_{crit}$ the opacity of the infalling material is negligible except at radio wavelengths, and the flow pattern is unlikely to be confused by such complications as radiation-driven winds.

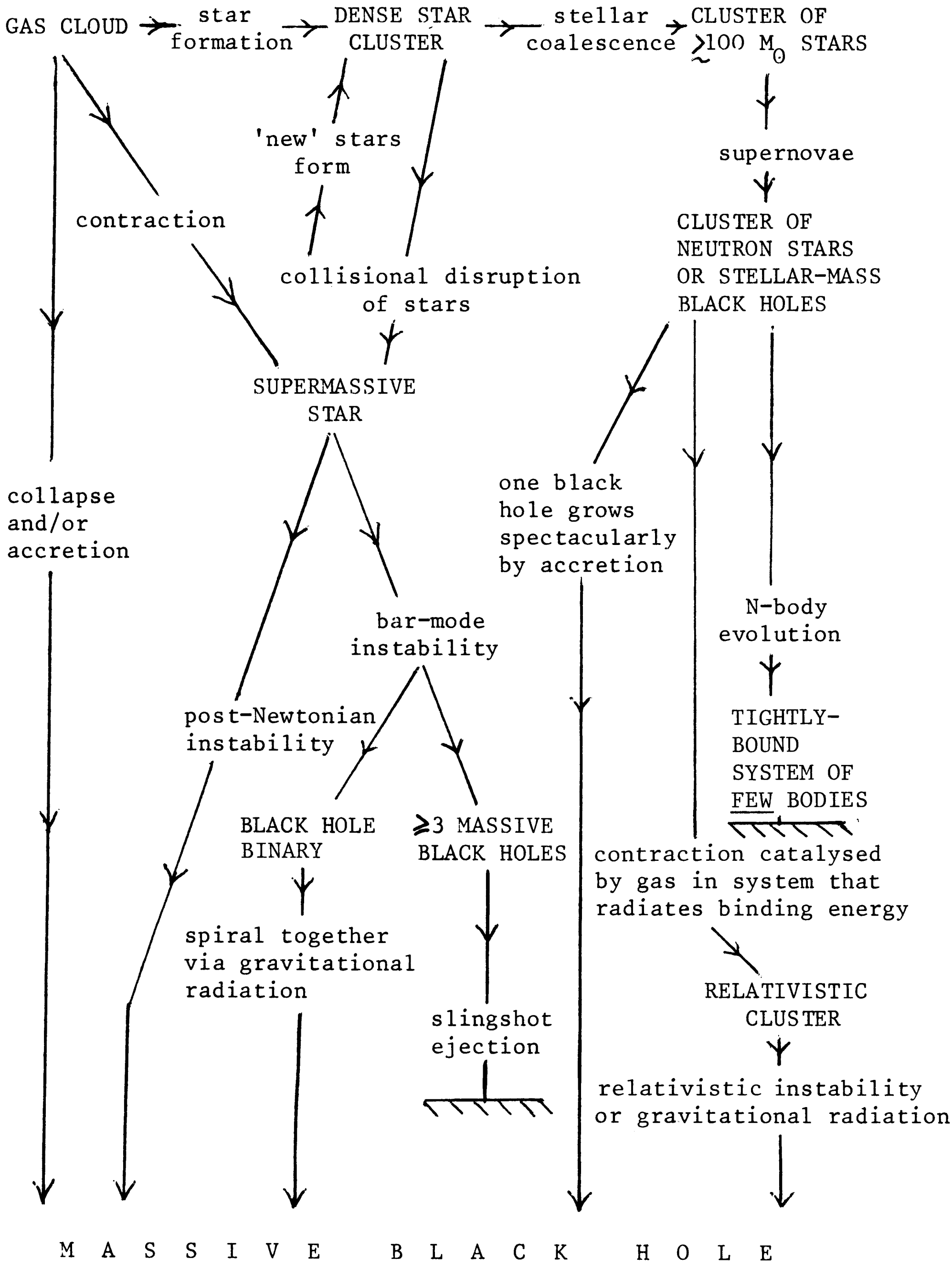

Figure 1. Scenarios for the formation of a massive black hole in an active galactic nucleus.

There are three general types of mechanism which could generate a non-thermal spectrum of relativistic electrons:

(i) Processes associated with magnetic flares or reconnection in a disc (Shields and Wheeler 1976) or in quasi-spherical inflow (Meszaros 1975).

(ii) Shock waves occurring near the hole, where the velocities are a good fraction of c (Fabian et al 1976). (It is known that shocks in supernova remnants, where the velocities are only 0.02c, are capable of accelerating relativistic electrons; and whatever process operates there should work even better when the velocities involved are higher.)

(iii) Exotic electromagnetic processes leading to production of electron-positron-pairs near a Kerr black hole (Blandford and Znajek 1977).

Electrons resulting from any of the above mechanisms would emit radiation via the synchrotron or inverse Compton process. Note, as regards (i), that the demands made on such a process are less severe when even the 'thermal' particles may themselves be mildly relativistic than in (e.g.) solar flares where the temperatures are much lower.

If the radio emission were synchrotron radiation, then self-absorption would require the effective emitting surface to have dimensions $\gg r_s$ (except possibly in the case of the Galactic Centre, where the power is only $\sim 10^{33}$ erg/sec). There are no cases where the current brightness temperature limits from VLBI are embarassingly high. On the other hand, it would by no means be surprising if some coherent radiation process operated in the very strong magnetic fields expected near accreting black holes. Synchrotron or inverse Compton radiation in the infra-red, optical or x-ray bands could in principle emerge from a region as small as $\sim r_s$, displaying correspondingly rapid variability. It still seems an open question whether the x-ray flux is more likely to be inverse Compton (Grindlay 1975) or thermal bremsstrahlung (Fabian et al 1976).

3. SOME SPECIFIC OBJECTS

The Galactic Centre

The very compact radio source at the Galactic Centre (Kellermann et al 1977) is much less powerful than the nuclear sources in, for instance, M81 and M82. Its properties make it most unlikely to be either a pulsar or a supernova remnant, though one cannot so readily exclude the possibility that it is an object of the same class as Cygnus X3. The recent observations of the infrared Ne line, discussed elsewhere at this meeting, place an upper limit of $5.\ 10^{6}$ solar masses on a hypothetical central black hole (which means that our Galaxy is unlikely to have ever experienced a phase of really violent radio or quasar-like activity). Accretion onto such an object could however provide a natural explanation for the radio component, and maybe also for some of the other phenomena occurring in the same region (Lynden-Bell and Rees 1971). If the radio source were the only manifestation of accretion, the required inflow rate would be only $\sim 10^{-14}\ \varepsilon^{-1}$ solar masses per year. The same source could perhaps be contributing to the infra-red flux from the Centre, in which case variability on timescales down to minutes could occur.

Centaurus A

Although the total radio power output of Cen A is only $\sim 10^{42}$ erg/sec, the energy stored in the very extended radio lobes is $\gtrsim 10^{60}$ ergs. This suggests that, when in its prime, Cen A might have been as spectacular an object as Cygnus A or 3C 273. If this energy were generated by a black hole (or its progenitor) the mass would be 10^8 solar masses, assuming reasonable efficiencies. The very compact central radio source, and the $\sim 10^{44}$ erg/sec variable x-ray source, can be explained in terms of accretion onto such an object (Fabian et al 1976). If this interpretation is correct, Cen A is the nearest galaxy that displays evidence of accretion onto a black hole at an abnormally high level.

M 87

Recent photometry of the central region of M87, together with evidence that the stellar velocity dispersion rises towards the centre, is suggestive of the presence of a central 'dark mass' of 10^{10} solar masses (Young 1977). Several hypotheses are consistent with the present tentative data, but one obvious possibility is that this mass constitutes a black hole, which could be the remnant of a violent outburst in the past. A hole as large as this would swallow stars whole, without tidally disrupting them; but it would be worthwhile to attempt to interpret the peculiarities of M 87's nucleus on the basis of the black hole hypothesis (c.f. Lynden-Bell and Rees 1971).

4. SOME OBSERVATIONAL QUESTIONS

(i) The magnetic fields in these compact radio components may be higher than in the central components of quasars and strong radio galaxies. The lower limits to surface brightness (proportional to $B^{-\frac{1}{2}}$ for a self-absorbed source) which can be set by VLBI measurements may therefore set significant constraints on models.

(ii) In the case of the weak source at the Galactic Centre, the magnetic field may be so high in the emitting region that circular polarization could be detected.

(iii) At the moment it is unclear whether the variable x-rays from Cen A (and also from other extragalactic sources such as 3C 120 and 3C 273) is thermal or non-thermal. Detection of a broad, variable (and possibly gravitationally-redshifted) x-ray Fe line would clinch this question, and also provide firmer evidence for the existence of a relativistically deep potential well.

(iv) The detection of variability on timescales down to r_s/c would be expected according to the black hole hypothesis in all bands except the radio.

(v) Statistical studies of variability could test whether there is evidence for any outburst of standardized energy, such as might be attributed to supernovae, or to stars being disrupted and swallowed by a black hole.

(vi) Correlations between spectrum, luminosity, variability, etc. could in principle help to decide how the observed properties of the nuclei depend on the hole mass, on $\dot{M}$, and on the angular momentum or other properties of the infalling material.

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DISCUSSION FOLLOWING REVIEW IV.4 GIVEN BY M.J. REES

APPENZELLER: I would like to comment on one of the processes for producing black holes indicated in your "flow diagram": As you know Dr. Klaus Fricke and myself have carried out detailed model computations for the consequences of the relativistic instability of massive objects. The results do not agree with your diagram. If you start with an equilibrium supermassive star ($10^5 \lesssim M/M_\odot \lesssim 10^9$) and make it unstable by either adding mass or by removing angular momentum, the object will explode rather than collapse to a black hole. Thus, the relativistic instability will normally lead to explosive events (which are observed in active galaxies) but not to the formation of massive black holes.

REES: Yes, I agree. This possibility should be represented by an extra arrow in my (already overcomplicated!) "flow diagram".

SHU: I have a question in connection with your comments on mass ejection being a natural expectation of this model. How does mass ejection occur simultaneously with mass accretion, especially in a spherical geometry? Could you elaborate how you visualize matter both to come and go?

REES: There must obviously be some deviation from strict spherical symmetry. One possibility is that inflow occurs in an equatorial plane, with outflow along a rotation axis (as in the "turn exhaust" radio source model); another possibility is that one has a turbulent or "two phase" mixture of rising and falling elements. Of course, the net flow must always be inward if accretion is the power supply.

WAXMAN: Concerning the simultaneous accretion and ejection of matter from an initially spherically symmetric accreting hole, we should realize that as the luminosity approaches the Eddington limit, the radiation field might be thought of as a "fluid". Then the radiation - gas interface may go unstable in analogy to a Rayleigh-Taylor instability yielding both channels of infalling matter and channels of outpouring radiation which may carry some matter with it.

REES: Yes. We would expect fluid elements where p_{rad}/p_{matter} exceeds the average value to develop into jets or bubbles. When this happens, there is of course no reason why the Eddington limit should not be exceeded.

OORT: You have made suggestions for the interpretation of many phenomena connected with nuclear activity, and it seems ungrateful to ask whether you could suggest an explanation for one more phenomenon, viz. the tendency for intermittancy in the expulsions observed. In the motions of the large molecular complexes near the Galactic center time scales of the order of a million years are suggested. And similar time scales occur in the emission of radio blobs in some radio galaxies, in particular some head-tail ones.

REES: Possibilities might include: (1) the interval between the disruption of successive stars by a massive black hole, (2) the time scale of gas flows in the Galactic nucleus, or (3) the time scale for gas accumulating in a potential well to become so dense that its cooling time becomes less than its free-fall time, leading to sudden infall. But none of these mechanisms leads to a natural time scale of a million years.

VAN DER LAAN: Your lecture casts doubt on the appropriateness of the ratio of "living/dead" nuclei of galaxies and quasars with which it began. A large range of temporal variations for any one nucleus' power seems implied by the physical scenarios you sketched, with potential activity depending only on appropriate fuel. If you must retain a biotic metaphore, perhaps the ratio "awake/asleep" is preferable.

REES: It is unclear whether low-luminosity galactic nuclei represent slowly-dying quasars, or whether they have never been luminous. It is also possible that some "dormant" black holes may be "revived" if they receive a renewed gas supply. (The work of Condon and Dressel suggests that this may happen in disturbed interacting systems.) I agree that "awakening" is a more appropriate term for this star "resurrection"!

CAPACCIOLI: In addition to what you said about M87, I like to mention that near the center of NGC 3379 de Vaucouleurs and I found a strong excess of light with respect to the requirements of the isothermal model. This excess has been analyzed using the model worked out by P. Young and is consistent with the presence of a nuclear "black hole" having a mass of 4×10^8 $M_\odot$.