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ON QUASARS, DUST AND THE GALACTIC CENTRE

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SUMMARY

The black-hole model of galactic nuclei is used to discuss properties of quasars as proto-black-holes in the middle of galaxies. Quasar life-times may be as long as $\sim 10^8$ years and masses will be of the order of $10^8 \, M_\odot$. Dust in the neighbourhood of black holes is sometimes driven from the accreted gas by radiation pressure. This may cause the dust often seen in exploding nuclei and the infra-red radiation from the galactic centre. Dust models for the galactic centre are considered in detail, and it is suggested that there may be a central black hole currently emitting $\sim 1 \cdot 5 \times 10^8 \, L_\odot$ in the ultra-violet and blowing away a hot nuclear wind. Emission knots in the central regions probably contain prominent OB stars which would make the Galaxy later than Sb. Finally we list critical observations which could establish the existence of a large central mass in the Galaxy of so small a size that it must be associated with a black hole.

1. INTRODUCTION

Earlier one of us explored the statistics of dead quasars (both radio quiet and loud) and concluded the average distance between such objects might be about 3 Mpc. This led to a model of galactic nuclei (1) in which each dead quasar disappears down its Schwarzschild throat and is surrounded by stars. On this model the main source of subsequent activity turns out to be the slow accretion of gas which circulates and slowly runs down into the central black hole just as water runs out of a bath. Such a model was first considered by Salpeter (2). The reason for the slow inward motion is that viscosity in the differentially rotating gas in the galactic plane causes a flow of angular momentum outwards, and the balance between centrifugal force and gravity then leads to an inward flow of the matter of the inner parts towards the Schwarzschild mouth. It was argued that the viscosity was probably magnetic in origin, but whatever the detailed form Salpeter showed that 1/18 of the rest mass energy of the inflowing material is liberated via the viscosity. When the accretion of angular momentum into the singularity is taken into account the Schwarzschild metric becomes a Kerr metric, which on further accretion tends to the limiting case in which the ratio of angular momentum to the square of the mass is Gc^{-2}. Bardeen (3) and others (4) have shown that for this (more likely) rotating singularity nearly 42 per cent of the accreted rest mass energy is emitted. Our calculations will be for this Kerr metric situation. Salpeter pointed out a fundamental limit to the rate at which the mass of the Schwarzschild throat can grow. The power radiated is $\sim 1/18$ of the inward rest mass energy flux, so the rate of growth of the central mass, per unit mass, is directly related to the luminosity-to-mass ratio of the object. If this exceeds $\sim 3 \cdot 10^4$ of the solar luminosity-to-mass ratio, electron scattering in the ionized material produces sufficient opacity for radiation pressure to overcome gravity. Similarly, dusty material like interstellar gas will get blown away for luminosity-to-mass ratios exceeding 100. These considerations applied to the Schwarzschild case led to the ' Salpeter limit ' on the growth rate of the central mass of $M/\dot{M} \gtrsim 2{\cdot}8 \times 10^7$ years for ionized material. The similar results for our Kerr metric is $M/\dot{M} \gtrsim 3{\cdot}6 \times 10^8$ years. Both limits can be increased by a factor of 300 for dusty material if the dust does not evaporate before being blown away. In either case it is unlikely that a small black hole could grow into a large one by ravenously eating interstellar gas, because the time scale would be too long.

A way around this difficulty is to assume that there was initially not a central mass but rather a concentration of material in a differentially rotating sheet of gas. Star formation may have been inhibited in the central regions of a proto-galaxy, either because strong differential rotation strengthens the magnetic field, or because of the high turbulence there. A further possibility is that the opacity in the central regions of a proto-galaxy may be high enough for radiation pressure to impede the condensation of stellar masses. As such a spinning disc of gas shrinks due to the action of friction, the dissipation increases and the temperature rises until the body approaches the limiting luminosity-to-mass ratio of $3{\cdot}10^4$. Thereafter gravity is somewhat offset by radiation pressure so the evolution proceeds more slowly, the luminosity-to-mass ratio staying close to this critical value. The quasars, we believe, may be just such objects. If the critical mass-to-light ratio of $(3 \times 10^4)^{-1}$ is assumed, the mass of an object producing 10^{46} erg per second is $8{\cdot}10^7 M_\odot$. Since Bardeen & Wagoner (5) have found a limiting binding energy for such discs of 38 per cent of Mc^2, the available energy would be $0{\cdot}38 \times 8 \times 10^7 M_\odot c^2 = 4{\cdot}10^{61}$ erg. At 10^{46} erg s^{-1} this gives quasar life times of the order of $1{\cdot}3 \times 10^8$ years. However that number would be reduced if a large fraction of the energy were emitted explosively, or if quasars emitting 10^{46} erg s^{-1} are blowing themselves apart by radiation pressure at the same time. In the latter case the quasar absorption lines might find a natural explanation.

2. DUST NEAR BLACK HOLES

For the case of steady accretion by a collapsed object, the luminosity is related to the rate of infall of matter F_{-3} (measured in the convenient units of 10^{-3} solar masses per year) by

$$P \simeq 2{\cdot}2 \times 10^{43} F_{-3} \text{ erg s}^{-1}.^{*} \tag{1}$$

The emission is strongly concentrated towards the centre (more so than in the Schwarzschild case) but for large values of the parameter

$$m_0 = r/(GM/c^2) \simeq r_{\text{pc}}/(4{\cdot}7 \times 10^{-6} M_7)$$

the locally-generated power is

$$p(r) = 2{\cdot}6 \times 10^{18} m_0^{-3} F_{-3} M_7^{-2} \text{ erg cm}^{-2} \text{ s}^{-1}. \tag{2}$$

M_7 is the gravitational mass of the central object in units of 10^7 solar masses.

Some of the energy $p(r)$ will be transformed into relativistic particles, which will subsequently radiate via various non-thermal mechanisms. Most of the radiation, however, will be emitted thermally by gas or dust. In order to discuss the spectrum

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* This is higher by a factor ~7 than the value quoted by Lynden-Bell (1) because we are now assuming that the black hole is described by a Kerr metric. For this reason (and also because of a reduction in our estimate for the efficiency of magnetic friction) the numerical values of various other quantities quoted here will differ from those given in the earlier paper.

of this radiation, we need to investigate the likely physical conditions in the disc in more detail. We use the same notation as (**1**): $V_c \simeq 3 \times 10^5 m_0^{-1/2}$ km s^{-1} is the circular velocity; c_s is the ' sound speed ' in the disc, allowing for magnetic, turbulent and thermal gas pressure; and the disc thickness is $(c_s/V_r)r \simeq (x/20)r$. We shall take the magnetic friction to be ~ 10 times lower than in the earlier work, to take account of the tendency for the field to become strongly aligned in tangential directions. These assumptions lead to inward velocities of

$$V_r \simeq 30\ m_0^{-1/2} x^2 \text{ km s}^{-1}. \tag{3}$$

The mean particle density $\bar{n}$ in the disc is then

$$\bar{n} \simeq 8 \times 10^{15}\ m_0^{-3/2} x^{-3} F_{-3} M_7^{-2} \text{ cm}^{-3}. \tag{4}$$

Under what conditions of temperature and ionization is the gas capable of radiating at the rate $p(r)$ required by (2)? If self-absorption is negligible, the maximum rate of radiation by a gas with normal ' solar ' abundances is attained at a temperature $T \simeq 10^5$ °K, and is $\sim 10^{-21}\, n^2$ erg cm^{-3} s^{-1} (**6**). This corresponds to a maximum mean surface luminosity for the disc of

$$\sim 5\cdot 10^{20}\ m_0^{-2} x^{-5} F_{-3}^2 M_7^{-3} f^{-1} \text{ erg cm}^{-2}\text{ s}^{-1} \tag{5}$$

where $f = \bar{n}^2/\overline{n^2}$ is the ' filling factor '. An upper limit to the possible ' degree of clumpiness ' can be estimated if we calculate the density enhancement that is needed for thermal gas pressure alone to balance the total magnetic and turbulent pressure. This yields

$$\left.\begin{array}{ll} f \simeq 1 & m_0 \gtrsim 10^7 x^2 \left(\dfrac{T}{10^4}\right)^{-1} \\ f \simeq 10^{-7} x^{-2} \left(\dfrac{T}{10^4}\right) m_0 & m_0 \ll 10^7 x^2 \left(\dfrac{T}{10^4}\right)^{-1} \end{array}\right\}. \tag{6}$$

Comparing (5) with (2), we find that the gas is able to radiate the necessary energy provided that

$$2 \times 10^8\ M_7^{-1} x^{-3} F_{-3} \gtrsim 1, \tag{7 a}$$

if f is given by (6). If, however, $f \simeq 1$ throughout the disc, we obtain

$$200\ m_0 x^{-5}\ M_7^{-1} F_{-3} \gtrsim 1. \tag{7 b}$$

Thus the condition is satisfied except for large central masses and low inflow rates. In particular, even the condition (7 b) (appropriate when the gas is not clumpy) would be fulfilled for a disc at the galactic centre, which, as discussed in more detail in Section 4, might have $M_7 \simeq 10$ and $F_{-3} \simeq (10^{-2}\text{–}10^{-1})$. We shall return later (Section 3) to the behaviour of discs where (7) is violated: this situation may be relevant to extra-galactic X-ray or radio sources. When (7) is satisfied by a large margin, the gas would be at $\sim 10^4$ °K and partially ionized (unless self-absorption were important, and necessitated a higher temperature in order to avoid violating the blackbody limit).

The energy released by the inward-spiralling material would thus emerge in the optical or near ultra-violet region of the spectrum, unless it were subsequently absorbed by dust, and re-radiated in the infra-red. The infalling matter would consist of dust as well as gas—if the composition were similar to that of interstellar matter, dust would constitute ~ 1 per cent of the total mass. Even if the grains consisted of a refractory substance such as graphite, they would not survive at temperatures $\gtrsim 2000\,^\circ\mathrm{K}$. The equivalent blackbody temperature is

$$T_2 \simeq 2{\cdot}6 \times 10^5\, m_0^{-1/2} F_{-3}^{1/4} M_7^{-1/2}\,^\circ\mathrm{K} \tag{8}$$

so the condition $T_2 \simeq 2000\,^\circ\mathrm{K}$ corresponds to

$$m_0 \simeq 1{\cdot}7 \times 10^4\, F_{-3}^{1/2} M_7^{-1}. \tag{9}$$

The fact that very small grains emit very inefficiently at long wavelengths, and are consequently hotter in a given radiation field than a blackbody would be, means that they would actually evaporate at a larger value of m_0 than given by (9). Radiation pressure may however, drive the grains out of the disc before they become hot enough to evaporate. Instead of being swallowed up with the gas, the dust would then accumulate in the environs of the central black hole. This possibility would have a variety of interesting consequences, and we explore it quantitatively below.

A dust grain of effective cross-section σ uniformly illuminated from one hemisphere feels a radiation force of $\frac{2}{3}(\sigma/c)\mathbf{S}$, where $\mathbf{S}$ is the energy flux vector of the radiation. Grains will therefore drift relative to the gas at a speed such that this force is balanced by collisions with gas atoms. If the grain travels *sub*sonically, with velocity v_g, the number of atoms colliding per unit time is $\sigma_{\mathrm{coll}} n c_s$. σ_{coll} is the effective collision cross-section (which may be much larger than the geometrical cross-section σ if the grains are charged and the gas ionized). Owing to the grain's motion, each collision imparts an extra momentum to the atom which is, on average, about $m_H(v_g - v)$, where m_H is the mass of an atom and $(v_g - v)$ the velocity of the grain through the gas. Hence the drag is

$$-\sigma_{\mathrm{coll}} n c_s m_H (v_g - v). \tag{10}$$

For a supersonic grain, c_s must be replaced by $|v_g - v|$ in (10).

We consider first whether the pressure of the locally-generated radiation can drive the grains out at right angles to the disc. For particles of radius a in the range 10^{-4}–10^{-5} cm appropriate for interstellar grains, it is easily checked that gravity is negligible compared with radiation pressure in situations of interest to us here. If the grain is to escape,

$$v_g/v_r \gtrsim \frac{x}{20}. \tag{11}$$

For the subsonic case, with $n = \bar{n}$ and $T \simeq 10^4\,^\circ\mathrm{K}$,

$$v_g = \left(\frac{2}{3}\frac{\sigma}{c}p\right)\Big/(\sigma_{\mathrm{coll}} n c_s m_H) \simeq 1{\cdot}2 \times 10^4\, m_0^{-1} x \left(\frac{\sigma}{\sigma_{\mathrm{coll}}}\right),$$

so (11) requires

$$m_0 \lesssim 1{\cdot}2 \times 10^4\, x \left(\frac{\sigma}{\sigma_{\mathrm{coll}}}\right). \tag{12}$$

Two processes cause each grain to acquire an electric charge: (i) initially uncharged grains would have a greater probability of accreting electrons than protons (because the former move faster), so they acquire a *negative* charge which suffices to bring the two accretion rates into balance; and (ii) ejection of photoelectrons leads to a positive charge on grains, which can be substantial if they are exposed to intense ultra-violet radiation. For an ionized gas at $\sim 10^4\,^\circ\mathrm{K}$, (i) leads, according to Spitzer (**7**), to a charge of $\sim -150(10^5 a_{cm})e$. The importance of process (ii) is sensitive to the radiation spectrum, but charges of up to $+5000(10^5 a_{cm})e$ are possible (**8**). It is unlikely that these two processes would exactly cancel out, so we might expect charges of $|100\text{–}5000|(10^5 a_{cm})$. If the gas were completely ionized, these charges would increase the effective collision cross-section σ_{coll} to $(100-2\times10^5)$ times σ, reducing v_g by a corresponding factor. Taking this into account, (12) shows that it is unlikely that the radiation pressure associated with the local emission $p(r)$ (equation (2)) can drive grains out of the disc.

If the radiation from the central regions could penetrate out *through* the disc to a radial distance corresponding to m_0, it would provide a pressure $\sim m_0$ times higher than the transverse pressure due to the locally-generated radiation field. However, this radiation would only affect dust at m_0 provided that it is neither (a) absorbed by dust closer to the centre, nor (b) scattered out of the disc (or absorbed) by gas at smaller values of m_0. The optical depth along the disc due to electron scattering is

$$\tau_{\text{scat}} \simeq 4\times10^3\, F_{-3} M_7^{-1} x^{-3} \tag{13}$$

(the main contribution coming from small m_0). This may well be $\lesssim 1$ (and would be so when the parameters have values appropriate to the galactic centre (see Section 4)). The disc may be optically thick in the Lyman continuum. However, if this is not so, and if $\tau_{\text{scat}} \lesssim 1$, the full pressure of the central source (with power given by (1)) would act on the innermost surviving dust. When the disc is homogeneous, this force will only be able to drive the dust radially outward until a layer of unit optical depth has built up. However the situation is different when the disc is inhomogeneous, as we expect it to be (from (7)) where $m_0 \lesssim 10^6$. The gas will then be concentrated into clouds, sheets or filaments occupying only a fraction $\sim f$ of the total volume. The radial radiation pressure need only then drive the grains out of the cloud in which they are situated, and the transverse pressure will then suffice to blow them free of the disc. Even if the radial dimension of individual clouds is taken as large as f times the disc thickness (the most pessimistic case), the condition is

$$\frac{\sigma}{\sigma_{\text{coll}}} \lesssim 1{\cdot}2\times10^4. \tag{14}$$

The grains will be blown out at the largest value of m_0 at which the gas is concentrated into clouds, provided that (14) is satisfied.

It is clear from (**1**), and from the foregoing, that infalling discs are capable of providing the energy source for violent and compact extra-galactic phenomena. The energy would be channelled into optical and ultra-violet thermal emission (and perhaps, via the magnetic dissipation, into relativistic particles). If this radiation is absorbed by dust, it will eventually emerge in the infra-red, and we have seen that an unusually high dust-to-gas ratio may result from the possibility that dust grains may be expelled from the disc and ' recirculated ', whereas the gas would stream downward into the singularity. In Section 4, we indicate how these ideas might apply to the specific case of the galactic centre, but before doing so we shall briefly mention a further aspect of the rotating disc model which may be relevant to other extra-galactic ' violent events '.

3. OVERHEATED DISCS

When inequality (7 b) is violated, the disc is incapable of radiating the energy dissipated if it remains at $T \lesssim 10^5\,^\circ$K. However, the cooling efficiency of a gas drops off at temperatures above $10^5\,^\circ$K, and does not attain a value as high as the peak at

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$\sim 10^5\,°$K until the gas is so hot that the electrons are relativistic ($T \gtrsim 10^9\,°$K). Therefore, a disc which cannot satisfy (7 b) at $T \lesssim 10^5\,°$K has no alternative but to heat up drastically. Moreover, inspection of (7 b) reveals two additional effects which enhance this instability.

(i) At high gas temperatures, thermal pressure alone can thicken the disc, so x increases. This increases the magnetic friction, which increases the inflow rate and reduces the density, so the gas becomes even less capable of radiating.

(ii) Even if f was initially $\ll 1$, it increases as T rises, and this also has a destabilizing effect. This suggests that discs which cannot radiate efficiently enough at 10^4–$10^5\,°$K will blow up into spheres. It is unclear whether these should be identified with thermal X-ray sources, or non-thermal radio sources, but it is interesting that with sensible parameters $M_7 = 10^3$ and $F_{-3} = 1$ the central region of M 87 will violate (7 b).

4. THE GALACTIC CENTRE

Detailed studies of our galactic centre in the radio and infra-red regions of the spectrum show that few of its properties are unique within the Galaxy. Rather they are more extreme examples of phenomena known elsewhere. Second only to the centre in most attributes is the huge H II region Sag B2 = G 0·7. This source is as

TABL

Name	Ref.	Radius: Angle	Radius: Size	Brightness distribution	Wavelength
Radio fine structure	(a)	$\lesssim 5''$	0·3 pc?	2 points E–W?	6 cm
Nuclear infra-red	(b, c)	$8''$	0·4 pc	$r^{-0\cdot8}$	5–20 μ
Nucleus	(b)	$1\cdot5'$	4·5 pc	$r^{-0\cdot8}$	1–3 μ
Nuclear 100 μ	(c)	$\lesssim 1\cdot5'$ $10'$	$\lesssim$ 4·5 pc 30 pc	— —	70–100 μ
Sagittarius A	(d, e, f, g)	$1\cdot8'$	5 pc		2–10^3 cm
Extended thermal source	(d, h)	$30'$	90 pc	1°×0·4°	2–70 cm
Thermal clouds	(d, i)	$<40'$	< 120 pc	$6'\times4'$	2–70 cm
G(−0·6, −0·1)	(c, d, i)	$35'$	100 pc	$5'\times3'$	10 cm 70 μ
G(0·7, 0·0) Sag B	(c, d, i)	$40'$	120 pc	$5'\times2'$	10 cm 80 μ
OH clouds	(j)	$50'$	150 pc	0·5°×0·4°	18 cm
Extended non-thermal source	(d)	1·5°	270 pc	3°×1°	300 cm
Continuum ridges	(k)	$\frac{1}{2}$–2°	360 pc	—	20 cm
21 cm forbidden velocities in plane	(l–o)	2° & 5°	900 pc	2°×1°	21 cm
Disc & ring	(k, n, o)	2° & 4°	720 pc	4°×$\frac{1}{2}$° & 8°×$\frac{3}{4}$°	21 cm
Hα at −180 km s^{-1}	(p)	2° & 3°	540 pc		Hα
High velocity clouds	(m, o, q)	4°	720 pc	1°	21 cm
Extended 100 μ	(r)	3°	540 pc	6°×2°	$\sim$100 μ
Expanding arm	(n)	20°	4 kpc	40°×1°	21 cm
γ-ray enhancement	(s)	$\lesssim$ 20°	$\sim$4 kpc	40°× < 30°	10^8 ev ($\sim 10^{-12}$ cm

strong as the galactic centre in the far infra-red. It has stronger compact radio continuum components and recombination lines, but lacks the non-thermal emission which is the dominant large scale feature of Sag A. There is no evidence of a high velocity nuclear wind blowing out of G 0·7 as there is out of Sag A.

However although this weakens the case for the uniqueness of Sag A within the Galaxy it remains true that exaggerated forms of the type of activity shown there are the basis of the phenomena observed in Seyfert Galaxies, and these objects in turn show the attributes associated with N Galaxies and quasars in a muted form.

Two questions naturally arise:

1. Can we exaggerate normal forms of activity associated with stellar evolution, supernovae, etc., to explain the whole class of phenomena from H II regions to quasars?
2. Can we take theories of quasars and mute the activity proposed in them to produce phenomena not unlike those seen in the large H II regions?

Neither possibility seems to us to be so unlikely that it can be ruled out. The first naturally leads to the multiple supernova concept of a galactic nucleus in formation and, by extension, to McCrea's (9) multiple temporary superstars which are probably needed to explain those variations of quasars that involve too much power for ordinary supernovae.

I

Flux (f.u. [10^{-26} W m^{-2} Hz^{-1}] unless otherwise stated)	Spectrum	Interpretation	Mass [$M_\odot$]	Associated Energy [erg]	Power [$\times 10^{-33}$ erg s^{-1}]
~1	?	? Compact H II region?	—	—	—
800 ± 300 (20μ)	$\nu^{-2\cdot5}$	Dust + nuclear u.v. or	—	—	3×10^6
30 (2μ)	ν^2	starlight			
2×10^5		Stars	$4\cdot5\times10^7$	—	$1\cdot5\times10^7$
$(8\pm3)\times10^5$		Dust + nuclear u.v. or starlight			3×10^8
300 (10 cm)	centre $\nu^{-0\cdot25}$ outside $\nu^{-0\cdot7}$	Synchrotron	$\gtrsim 10^2$	10^{49}	$\gtrsim 10^2$
600 (10 cm)	$\nu^{-0\cdot1}$	H II, Nuclear u.v.	7×10^5	7×10^{52}	3×10^7
70 (10 cm)	$\nu^{\sim0}$	H II + Young Stars?	8×10^4	10^{52}	7×10^6
17 $1\cdot4\times10^5$	$\nu^{-0\cdot1}$ Peak	H II + Young Stars + Dust	4×10^3	3×10^{51}	5×10^7
60 $3\cdot2\times10^5$	$\nu^{-0\cdot1}$ Peak		6×10^3	4×10^{51}	8×10^7
—	—	—	—	—	—
2000? (300 cm)	$\nu^{-0\cdot7}$	Synchrotron	—	$\sim10^{49}$	$\gtrsim 10^2$
—	—	Synchrotron (B disturbed)	—	—	—
—	—	Nuclear wind	5×10^6	5×10^{53}	5×10^6
—	—	Circular motion	—	—	—
—	—	Nuclear wind		ionization motion	10^7 $3\cdot10^6$
—	—	Blobs in wind	5×10^6	2×10^{53}	2×10^6
—	—	Dust & starlight	—	—	$\gtrsim 10^9$
50 km s^{-1} (1 $M_\odot$ year^{-1})		Past explosion or nuclear wind	4×10^7	1×10^{54}	10^6
10^{-4} photons cm^{-2} s^{-1}	ν^{-2}?	Intense cosmic rays' bremsstrahlung?	—	—	4×10^4

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Notes on Table I

The masses were derived as follows: *Nucleus*, Becklin & Neugebauer's estimate of stellar mass inside a radius of 4·5 pc; *Sagittarius A*, this mass is necessary to bind the magnetic field and particle energy to the nucleus against its natural tendency to expand; the *extended thermal source's* mass is taken from Lequeux (d) who derived it from a radio estimate of the emission measure and the known dimensions; and the total mass of the thermal clouds is determined likewise. Masses from the 21-cm data are discussed in refs (o) and (n).

The energies for the *non-thermal sources* are derived from minimum energy requirements to produce the observed emission (d). The energy of the *extended thermal source* is a rough estimate of its kinetic energy, assuming a velocity of 100 km s^{-1}. The ionization energy is a factor of 70 smaller. Other energies in the table are kinetic.

The powers are either observed power in the radiation or, in the case of ionized material, they are the powers required to keep the material ionized. The calculations have been performed by relating the number of $H\beta$ photons to the known emission measure and deducing the total number of Balmer photons. We then assume that each Balmer photon is produced by one ultra-violet photon beyond the Lyman limit. A lower limit to the required power is deduced by placing every such ultra-violet photon *at* the Lyman limit, but we have multiplied this estimate by a factor ~ 3 to allow for photons redder than the Lyman limit and for the higher energies of some of the ionizing photons. The results of these calculations were checked against the recombination power of a fully ionized medium assuming that it is optically thin. This gave powers up to a factor 3 higher still. Note that this last calculation does not assume an ultra-violet ionizing mechanism, so powers comparable with those quoted here are required independently of the detailed ionization mechanism.

The powers for the expanding features were deduced from their total energies, expansion velocities, and distances from the centre by the formula $P=E/(R/V)$.

Interpretations have mainly been described in the text, but the attribution of the excitation of the thermal clouds to young stars is controversial since OB stars shun the nuclear regions of Sb galaxies. Nevertheless we find the round shape of these regions in the galactic plane difficult to explain if the ionization comes from the centre. Ionization from the kinetic energy of the nuclear wind is barely possible on energetic grounds. We deduce that OB star ionization is the most likely, so that our galaxy may be of somewhat later type than Sb. The rather excited state of the nuclear region is more often associated with some barred structure like that suggested on other grounds by Kerr (k) so we might prefer a designation for our galaxy like SAB bc.

The second suggests that the black-hole formation theory of quasars should be extended downwards to black holes of considerably smaller masses which may result from supernova explosions of very massive stars. The natural place to find such objects is in supernova remnants within regions of star formations where they will be born and will accrete rapidly. We still consider that the strongest argument for the existence of black holes in the nuclei of galaxies is the likelihood that black holes are formed when quasars die, coupled with estimates showing that the number of dead quasars is comparable to the number of major galaxies. If this many dead quasars do indeed exist, few astronomers would dispute that galactic nuclei are the most likely places to find them. It is in this spirit that we now consider a black-hole model for the galactic nucleus.

To apply these general considerations to the galactic centre we need to estimate the total energy output from the black hole and its surrounding disc, and also to make some estimate of the gravitational mass of the hole. With these aims in mind, Table I provides a condensed summary of the known phenomena in order of distance from the centre. The main features are illustrated in Figs 1–3. The phenomena

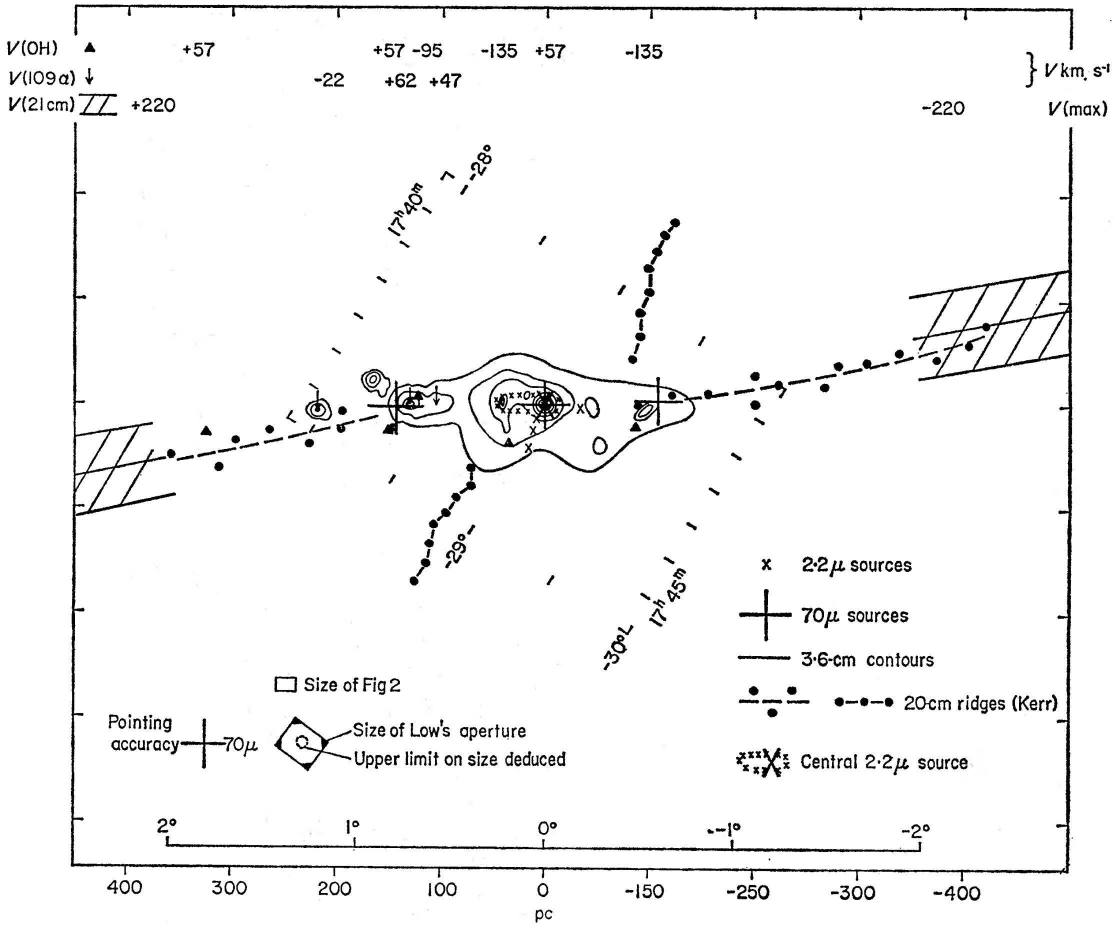

FIG. 1. *A schematic illustration of the radio, infra-red and optical data pertaining to the region within 2° of the galactic centre. Radial velocities are given at the top of the diagram. Epoch* 1950.

that are hardest to explain in terms of starlight alone are the ionization of the extended thermal source surrounding Sag A, and the ' nuclear wind ' which occurs in both ionized and neutral material, with outward velocities of order 200 km s^{-1}. Without changing figures by more than a factor 10, it would be possible to attribute all the infra-red radiation to re-emission of starlight by dust. However it is difficult to explain the presence of enough ultra-violet flux to ionize the extended thermal source and the nuclear wind. We shall therefore postulate an ultra-violet non-stellar continuum emanating from the environs of the central black hole, with a total power (in units of 10^{33} erg s^{-1}) of $P_{33} \simeq 6 \times 10^8$. This should be sufficient to supply both the far infra-red power, and the kinetic and ionization energy of the nuclear wind—the extended thermal source would be merely a portion of the nuclear wind. To generate this power from gravitational energy we need an inflow amounting to 3×10^{-5} solar masses per year (so $F_{-3} \simeq 3 \times 10^{-2}$).

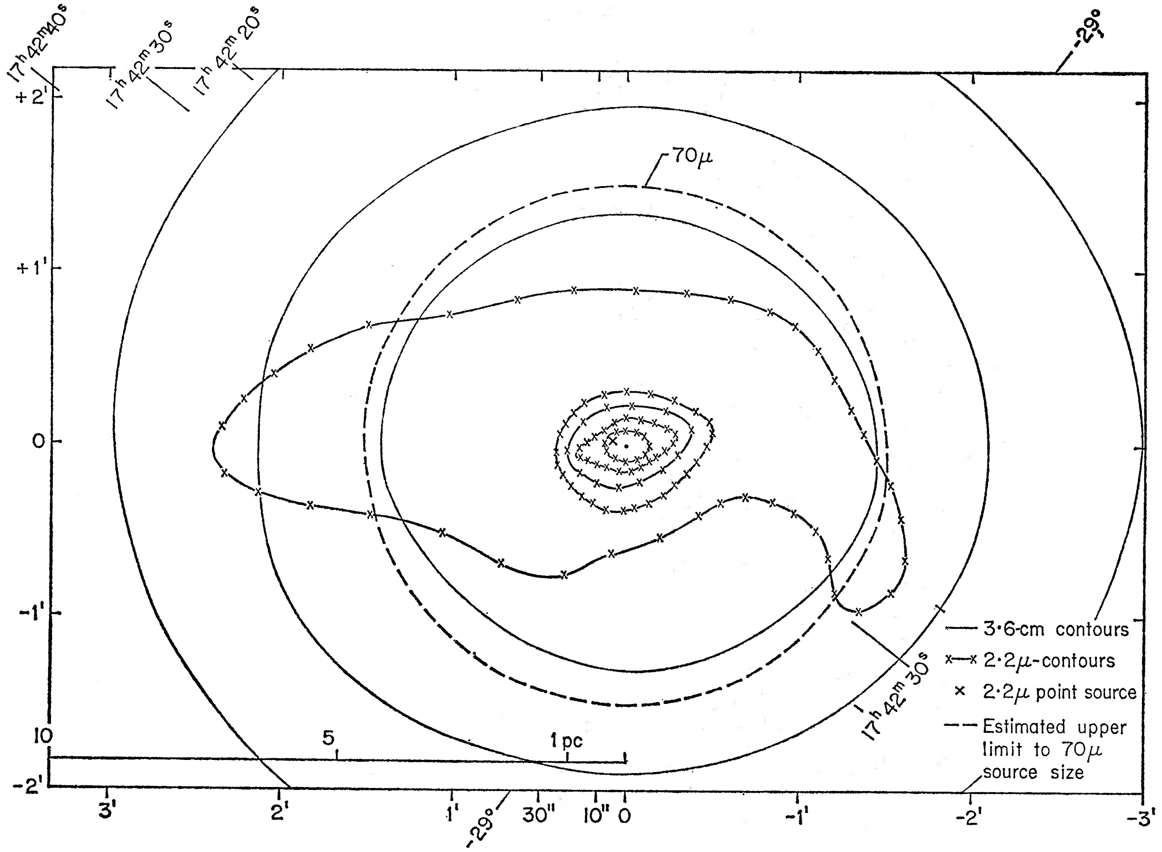

FIG. 2. *A magnified version of the central part of Fig.* 1, *showing the central infra-red and non-thermal radio emission. Epoch* 1950.

An interesting result of adopting a central source with about this power is that we may then account for the infra-red flux emanating from within 8″ of the centre (corresponding to a linear radius of ~0·3 pc). From the estimate of Becklin and Neugebauer, the colour temperature between 10μ and 20μ is of the order of 200 °K. However the flux at 10μ is only one thousandth of that from a blackbody 8″ in radius at that temperature. Thus, if the emitting region were roughly spherical, the optical depth of the dust at 10–20μ would be only $\sim 10^{-3}$. On the other hand, if the central continuum source had the power hypothesized above, the *ultra-violet* optical depth of the cloud would have to be $\sim 10^{-2}$. Unless the grains are even smaller than those known to exist in the solar vicinity, the effective absorption cross-section for ultra-violet radiation would be comparable with the geometric cross-section (i.e. $Q_{\mathrm{uv}} \simeq 1$). We therefore require that, at 10–20μ, $Q \simeq 0{\cdot}1$. If the extinction varied as λ^{-1} for wavelengths λ larger than the grain size a (as is found to be the case for local interstellar dust), this condition would require comparatively large grains, with $a \simeq 1\mu$. And it would in fact be unsurprising if grains near the Galactic centre tended to be large—if they had been ‘ cycled ’ through the disc in the manner suggested in Section 2, evaporation would have preferentially destroyed the smaller ones.

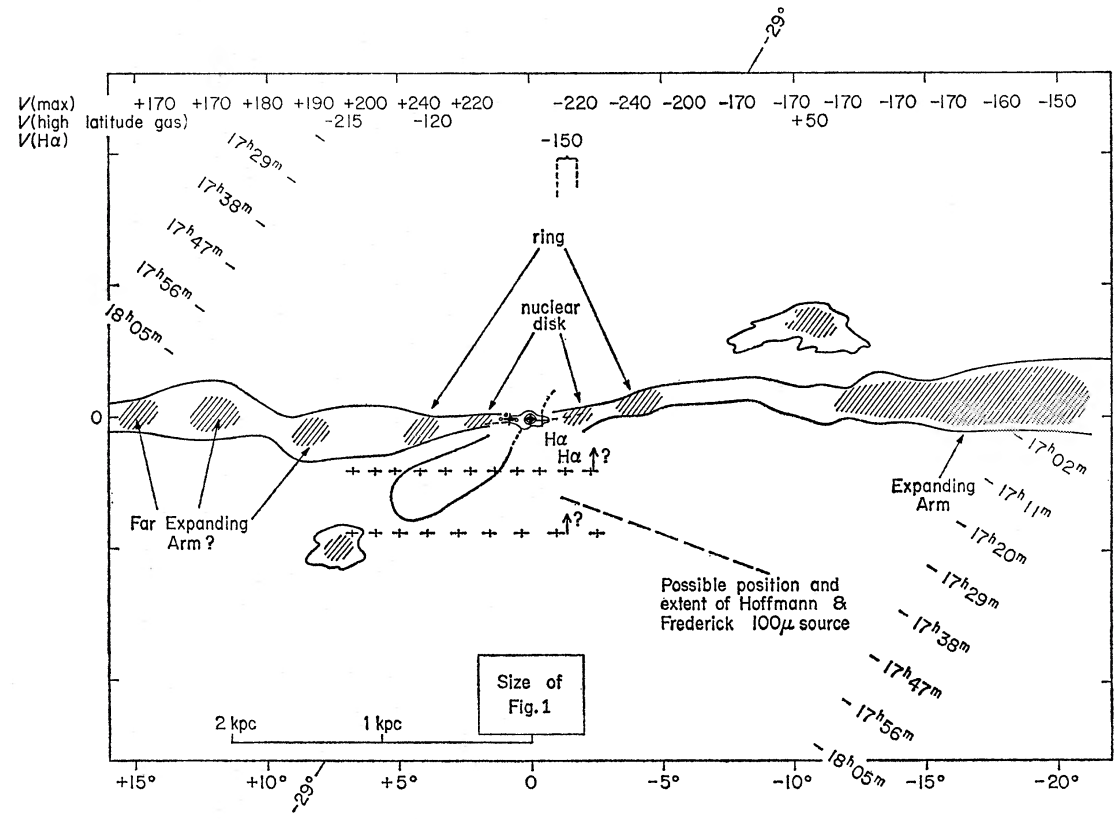

FIG. 3. *A general view of the galactic disc out to* ~ 4 *kpc from the centre. The region covered by Fig.* 1 *is indicated. Epoch* 1950.

However, the behaviour of Q in the infra-red depends on the grain composition (for example, silicates display characteristic emission peaks at $\sim 10\mu$ and at $\sim 20\mu$) so it is by no means essential to invoke especially large grains to explain the properties of the 10–20 emission from within 8″ of the centre. Observations with improved spectral resolution will obviously clarify this point. The above considerations regarding Q would still apply if the 10–20μ source were flattened or disc-shaped (as is indicated by the $2{\cdot}2\mu$ contours in Fig. 2): they would, however, be modified if the grains were concentrated into dense optically thick clumps (we shall return to this question in connection with the $\sim 100\mu$ emission).

Only ~ 1 per cent of the nuclear continuum provides sufficient power for the central infra-red source, and we have shown that, for plausible grain parameters, the absorbed radiation would be re-emitted with the observed spectrum. The bulk of the ultra-violet radiation escapes beyond 8″, and would be adequate to power the more extensive 70–100μ source studied by Aumann and Low. It is, of course, natural that grains further from the centre should be cooler, and should consequently radiate at longer wavelengths. We now explore this possibility in somewhat more detail. An important constraint on such models is that at least ~ 50 per cent of the ultra-violet radiation must penetrate even beyond the Aumann–Low source if it is to photoionize the extended thermal gas.

The total power in the 70–100μ band emerging from within $\sim 10'$ of the galactic centre is $P_{33} \simeq 3 \times 10^8$. About 25 per cent of this comes from a region $\lesssim 1{\cdot}5'$ (i.e. $\lesssim 4{\cdot}5$pc) in radius,* and the surface brightness decreases at larger radii (Aumann and Low, private communication). The spectral information is still very limited, but the peak flux density appears to occur at $\sim 70\mu$. We can use these data to infer the typical grain temperature. If each grain radiated like a blackbody, or if the emission came from optically thick regions, the temperature would be 43 °K. By comparing the observed power with the emissivity of a blackbody of angular diameter $3'$ we infer that the 70μ opacity out to a distance of 4·5pc is $\sim 0{\cdot}2$. (This is, of course, only a mean optical depth if the cloud is not spherically symmetrical.) The low-surface-brightness outer regions would not make a substantial addition to the total optical depth. For typical grains, Q decreases with λ, so their emission peaks at a shorter wavelength than would a blackbody at the same temperature. To allow for this, we should strictly have compared the spectrum with a blackbody somewhat *cooler* than 43 °K. The estimated infra-red opacity would then be rather larger.

If the grains were uniformly distributed around the central source, the requirement that at least half the ultra-violet radiation should escape to ionize the extended thermal clouds entails $Q(70\mu)Q/_{\mathrm{uv}} \gtrsim 0{\cdot}2$. Such high radiative efficiency in the far infra-red is unlikely unless the grains are exceedingly large, so it seems preferable to assume that the dust is concentrated in dense opaque patches with ‘ lanes ’ between them along which the ultra-violet photons can escape. This would also guarantee that the nuclear wind could stream outward without blowing all the dust away. There is a further independent argument that the dust may be patchy in its distribution: unless $Q(70\mu)/Q(2{\cdot}2\mu) \gtrsim 0{\cdot}2$, a uniform dust cloud would obscure the ‘ point ’ source detected by Becklin and Neugebauer at 2·2μ (which is probably due to stars close to the galactic centre). Thus two predictions of the dust model are that the unresolved part of the 70–100 source reported by Aumann and Low should not be substantially smaller than $3'$ in diameter, and that the infra-red emission should have a blotchy structure when viewed with high angular resolution, possibly splitting into several distinct clouds. One might also expect the outer parts of the source to have a ‘ softer ’ spectrum than the inner parts.

Dust models of this type probably gain in credence because of the presence of outlying 100μ sources coinciding with the H II regions $G+0{\cdot}7$ and $G-0{\cdot}6, -0{\cdot}1$ whose outputs are comparable with that from the unresolved part of Aumann and Low's source (see Table I). In this case the radiation may be due to re-emission of starlight, and the absence of a corresponding strong feature at shorter infra-red wavelengths is indicative of the lack of a strong localized source capable of producing a high radiation density. It is not clear to us that the sources found by Aumann & Low are not merely the brightest central parts of the very extended 100μ source

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* Aumann & Low assumed spherical symmetry in making this inference. The central concentration could be less marked if the emission came from a flattened source oriented along the galactic plane.

discovered earlier by Frederick & Hoffman. That source in turn is probably explicable in terms of a dust model (**10**), (**11**).

The inferred total mass of dust within G − 0·6, − 0·1 is $\sim 10(a/Q(70\mu))M_\odot$, when *a* is the dust grain radius in microns. This can be compared with the gas mass of $4 \cdot 10^3\, M_\odot$ estimated from the emission measure and size of the thermal radio source. The amount of dust within 4·5 pc of the galactic centre must be comparable with that in G − 0·6, − 0·1, though in this case we have no firm estimate of the total mass of accompanying gas, since much may be in molecular form. However, since we have argued that the galactic centre would naturally become enriched in dust, it need occasion no surprise if the dust-to-gas ratio has to exceed its value in the solar vicinity.

It is at present unclear how the nuclear wind is generated, but it seems not unlikely that *any* concentrated radiation source will be surrounded by a wind. The reason is that photons appropriate to the very hot innermost regions, where the matter is held in by strong gravitational fields, escape and interact with gas much further out. The electron temperatures cause by the deposition of the very 'hot' photons may be too great for the gas in these outer parts to be restrained by the weaker gravity. Thus an accreting black hole may undergo successive periods of slow accretion, followed by energy generation and ejection. On the other hand, a quasi-steady situation may be possible in which a fraction of the material in the inward-spiralling disc is expelled along the rotation axis by radiation pressure and escapes capture by the black hole.

It is worth remarking that there is an alternative to the ultra-violet excitation of the extended thermal source. A significant enhancement of cosmic rays in the central regions is necessary in order to explain the γ-ray data. If the enhancement amounted to a factor of 30, then an increase in magnetic field to $10^{-4}\, G$ could account for Sagittarius A, and the enhanced cosmic rays could ionize material with densities up to 10 particles per cc (even neglecting possible ionization by 'subcosmic' ray particles with energies below 100 Mev). Cosmic rays also provide a direct heat input into grains, but this is less important in general than the heating of grains by Lyman photons resulting from collisional ionization of hydrogen.

Currently there are no good data on which to base a mass estimate for the central black hole, since information on velocities $\lesssim 1$ pc from the centre is lacking. A central mass of $10^7\, M_\odot$ gives a circular velocity of 200 km s^{-1} at 1 pc. This value increases like $M^{1/2}$, and decreases with distance like $R^{-1/2}$. It seems that any value less than about $10^8\, M_\odot$ is compatible with present knowledge.

5. SPECULATIONS

The nuclei of Seyfert galaxies are known to be significantly reddened; great swathes of dust also seem to be a common feature among radio galaxies; and the spectra of some quasars and Seyfert galaxies show a peak in the far-infra-red. Can these effects be related to the sorting of dust from gas in the region surrounding a nuclear black hole?

Firstly, the dustiness of the Seyfert nuclei is a natural consequence of the idea that the radiation pressure near the black hole is too strong for dusty material to be swallowed. This should limit the mass-to-light ratios of these objects to between 10^{-2} and $3 \cdot 10^{-5}$ solar units. Further, the expulsion of material from these nuclei may also be a direct consequence of radiation pressure. In NGC4151 Cromwell &

Weymann (**12**) have suggested that the material is expelled from a region only $\sim 3 \cdot 10^{15}$ cm in radius, which also contains the source of the non-thermal ultraviolet continuum. This region would be too hot for dust to survive, so the ejected matter must be related to the nuclear winds found in the Galaxy and in M 31. Since in our model gas is secularly swallowed by the black hole, but the dust is blown back, it is conceivable that the nuclei of galaxies become unusually dusty. A violent explosion cleaning out the nuclear region would then shower the rest of the galaxy in one of the prominent dust clouds that are indeed associated with exploding galaxies. Some dust evaporation can provide elements for the more complicated molecules, and dust cooling can provide conditions propitious for their growth. This perhaps helps to explain why the galactic centre is one of the best places to detect radio molecular lines. (It also, incidentally, seems possible that molecules could contribute to the infra-red emission. This question should certainly be explored further, especially if future observations force us to discard or supplement dust models.)

6. CRITICAL OBSERVATIONS

In conclusion, we list various types of observation which could test the validity of the general ideas discussed in this paper.

1. The detection of one of the Kardachev higher recombination lines of hydrogen within $0 \cdot 2$ pc $\simeq 4''$ of the galactic centre would provide velocity determinations which could decide whether there is a mass of 10^7–10^8 $M_\odot$ situated there. The line should be 500 km s^{-1} broad and should shift by its own width between the two sides of the centre. 109α interferometry could achieve this. A possible alternative is a 21-cm interferometer survey of the galactic centre with high spatial resolution, but low (50 km s^{-1}) velocity resolution. This might show tenuous 1000 km s^{-1} wings on the 21-cm line within the central $8''$.

2. Very long baseline interferometry may soon be possible with a broad enough bandwidth to measure sources as weak as $0 \cdot 5$ f.u. to diameters of $10^{-3}{}''$. If so, it may be possible to determine the size of any central black hole that there may be in our galaxy. However H II may render the central source opaque with a greater angular size.

3. The diameter of Aumann & Low's unresolved 70μ source cannot be much less than $3'$ if a dust model is to fit. Mapping of this source from aircraft or balloons could determine this and test the reality of its separation from the large 100μ source.

4. Determination of the $A_B/E(B-V)$ ratio, and similar ratios in other colours, for the swathes of dust across radio galaxies should determine whether they consist of normal interstellar dust. Such work using calibrated photographic plates and photoelectric checks seems readily possible.

5. If the far-infra-red flux from the galactic centre displayed definite variability, dust models would plainly be inadequate. Systematic searches for variability in all strong infra-red sources are obviously of great importance.

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