PHENOMENA AT THE GALACTIC CENTRE - A MASSIVE BLACK HOLE?

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1. INTRODUCTION

About $10^7\ L_\odot$ of luminosity, mainly in ionizing flux and infrared radiation, emerges from the central pc^3 of our Galaxy. This exceeds the luminosity from the corresponding region of most nearby galaxies, though it is surpassed by M82 and NGC 253 (Reike and Lebofsky 1982), but perhaps involves nothing more exotic than a starburst 10^6 - 10^7 years ago. But the manifestations of activity at the Galactic Centre that are unambiguously non-thermal in character are at a much lower level: the γ-ray annihilation line ($\sim 10^{38}$ erg s^{-1}) and the compact radio source ($\sim 10^{34}$ erg s^{-1}). I shall comment briefly on these two phenomena, and also suggest an interpretation of the remarkable pseudo-spiral structures revealed by the NeII infrared and the radio-continuum maps. These phenomena relate to the old question (cf. Lynden-Bell and Rees 1971) of whether our Galaxy has ever experienced a more violent phase, leaving a massive collapsed remnant.

2. THE GAMMA-RAY SOURCE

The problems posed by the 0.511-Mev annihilation line have been reviewed by Lingenfelter and Ramaty (1983). The variability implies that the annihilations occur within a volume $\lesssim 10^{18}$ cm across, in gas clouds with density $\gtrsim 10$ particles cm^{-3}; the narrowness of the observed line implies that the gas must be cooler than $\sim 5 \times 10^4\,^{\circ}K$, with random internal motions $\lesssim 700$ km s^{-1}, but must nevertheless not be completely neutral (since, otherwise, the annihilation would occur via charge exchange, leading to a width $(\Delta\nu/\nu) \simeq (e^2/\hbar c)$). The line is not shifted from its expected 0.511 Mev energy: this implies that it cannot come from a compact region close to (say) a massive black hole - if there were such a hole of mass $10^6\ M_6$ solar masses, then the annihilation must occur $\gtrsim 10^{16}\ M_6$ cm from it.

The source of the positrons may, of course, be much smaller than the annihilation volume. Irrespective of its size, this source has the

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rather surprising property that its apparent luminosity over the entire X-ray and γ-ray band - from a few kev up to $\sim$ 1 Gev photon energies - is no larger than the power going into the annihilation line (i.e. into the rest mass of the pairs). This could imply any of the following three possibilities.

(i) The pairs are produced at energies of only $\lesssim$ 1 Mev. This could happen if there were a central source emitting primarily γ-rays, which was sufficiently compact that $\gamma + \gamma \rightarrow e^+ + e^-$ occurred. The requisite dimensions, for a pair luminosity $\sim 10^{38}$ erg s^{-1}, are $\sim 10^9$ cm. This would be smaller than the gravitational radius of a black hole unless its mass were below a few thousand solar masses (Eichler and Phinney 1983).

(ii) The pairs could be produced with high Lorentz factors but could lose their energy (before annihilation) via synchrotron radiation in the form of soft (optical or UV) photons. Even if all the ionizing flux came from this central source - and none from stars - the pairs would still need to form with $\gamma \lesssim 10^3$.

(iii) Much more continuum luminosity is perhaps being beamed along other directions than our line of sight. An elaborate model along these lines - the "gamma gun" - has been developed by Kardashev and Novikov (1983).

3. THE COMPACT RADIO SOURCE

The small central radio component is known to have an unusual (rising) spectrum. If there were a central hole with $M_6 \gtrsim 1$, then the radio emission could come from plasma participating in a low-level accretion flow and gravitationally bound to the hole (Rees 1982): if the plasma were unable to cool on the inflow timescale, then the only substantial radiative output would come from relativistic electrons at $< 10^3$ Schwarzschild radii, where even the average ion or electron could have > 1 Mev of kinetic energy and the field would be $10 - 10^3$ G. If there were no central mass larger than $10^3 - 10^4$ $M_\odot$, then the radio emission could come from a wind (Reynolds and McKee 1980, Kardashev 1983). While the compact radio source does not unambiguously require a massive black hole, the presence of such an object, accreting at a low rate, would almost inevitably yield radio emission - the absence of a peculiar radio source at the Galactic Centre would therefore have been evidence against a massive black hole there.

4. ARE THE PSEUDO-SPIRAL FEATURES TRIGGERED BY TIDALLY DISRUPTED STARS?

The stellar disruption rate due to a central hole depends on the star density within the central pc ; it could be as high as $10^{-3} M_6^{4/3}$ yr^{-1}, though loss-cone depletion effects may reduce this. (Note also that this rate is calculated on the assumption that there is indeed a dense star

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cluster at the Galactic Centre, which would not be obligatory if the infrared and the inferred UV radiation were due to black-hole accretion.) The fate of disrupted stars has been much discussed (see Rees 1982 and references therein). The original binding energy of the disrupted star must be supplied by its orbital energy: on average, therefore, the debris must be bound to the hole by an energy $\sim v_*^2$ per unit mass, v_* being the escape velocity from the surface of the star. However, as Lacy et al. (1982) emphasize, some fraction of the debris can escape at $\gtrsim 10^3$ km s^{-1}. The reason for this is that at peribothron a star undergoing tidal disruption is moving at $V_T \simeq 3 \times 10^4 M_6^{1/3}$ km s^{-1}: it becomes somewhat compressed and elongated into a prolate shape (cf. Carter and Luminet 1982) and pressure gradients can impart to material on the leading side of the star an excess velocity δv over the parabolic orbital velocity which is a significant fraction of V_*. This corresponds to a large excess orbital energy - enough for the debris to escape on a hyperbolic orbit with terminal velocity $\sim \sqrt{(\delta v) v_*}$. Whenever a star is disrupted, some fraction of its "remains" will spray out in a fan or cone. The linear features revealed by the NeII infrared and by the radio continuum observations (Lacy et al. 1982; Lo and Claussen 1983; Oort 1985) are perhaps indirect manifestations of these ejecta.

The pseudo-spiral features each involve several solar masses of material, moving with speeds $\sim$ 100 km s^{-1}; they are therefore not themselves composed of the high-speed ejecta. Nevertheless, the formation of these features may have been triggered by ejecta from a disrupted star - this at least seems a tenable alternative to the infall hypothesis favoured by Lo and Claussen (1983).

Suppose that the region within 1 pc is pervaded by predominantly photoionized gas with density $\sim 10^3$ cm^{-3}. [The emission measure from this gas (which may be deficient in dust (Gatley 1982)) would be swamped by that from the $\sim 10^5$ cm^{-3} concentrations within it.] Suppose - as an illustrative example - that each stellar disruption leads to the expulsion of $\sim 0.1\ M_\odot$ of material with velocities $\gtrsim 10^3$ km s^{-1} directed on a cone of solid angle $\sim 10^{-2}$ radius. By the time this debris has travelled $\sim$ 1 pc through gas of density $\sim 10^3$ cm^{-3} it will have swept up at least its own mass. The initial kinetic energy will thus have been turned into thermal energy, leaving an overpressured cone or swath of hot (> 10^6 $^{\circ}$K) gas along the path of the ejecta. The clouds of density $\sim 10^5$ cm^{-3} which delineate the observed pseudo-spiral features would then be produced as this overpressured material expands sideways, causing a radiative shock. (Conceivably the broad HeII emission (Hall et al. 1982) could be the only direct manifestation of the fast moving ejecta itself).

In this interpretation, the central parsec of our Galaxy could (though it need not) be in a steady state, averaged over timescales >> 10^4 yrs. Stellar disruptions every few thousand years (each leading to a $\sim 10^{44}$ erg s^{-1} flare lasting perhaps only a few years (Rees 1982)) would provide an energy input into the gas, clearing the central parsec of dust (Gatley 1982). The high-density clouds would then lie along the tracks of the most recent ejecta - those in which the overpressure has not been erased by cooling and by sideways expansion.

The apparent spirality might indicate some overall rotation in the ambient medium within the central parsec, as is obligatory in other interpretations of these features. If there were no such rotation, the debris from a disrupted star could in principle produce a curved track via an "aerodynamic lift" effect; the ejecta would generally not have a uniform momentum density per unit solid angle, so the shock where it interacts with the ambient medium would be oblique. (It would then of course be a coincidence, though only at the 25% level, that the three arms all curve the same way.)

5. CONCLUSIONS

The question of whether our Galactic Centre harbours a $\gtrsim 10^6\ M_\odot$ black hole - a question which bears on the relation between our Galaxy and the Seyfert galaxies - still cannot be settled definitely. Such a hole would account naturally for the compact radio component; it could also generate the $e^+ - e^-$ pairs inferred from the 0.511-Mev annihilation line, but this can be done more naturally by a $10^3 - 10^4\ M_\odot$ hole than by a larger one. If the pseudo-spiral features are triggered by directed expulsion of material rather than by infall, then tidal disruption of stars offers a possible explanation, and this would certainly require a mass $\gtrsim 10^6\ M_\odot$. It is still, however, open to sceptics to say that the best argument in favour of a massive black hole is that there is no firm evidence against it.

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DISCUSSION

B.F. Burke: What role is the compact radio source playing? Oort emphasized that it is not at the middle.

Rees: If it turns out not to be at the middle, then we have to say that either there is a large black hole giving the gamma rays and the radio source which is not at the dynamical centre of the spiral arms, or we have to say that the radio source is an irrelevance.

J.P. Ostriker: How many arms should the spiral have which is made by this star-disruption process?

Rees: If the spiral is due to ejecta, then naively one would expect just one arm per stellar flyby. If there is real evidence for symmetric ejection, then I prefer not to have this tidal-disruption mechanism, but to say that the jets are produced when a single star is being digested, and this gives us a thick-disk doughnut geometry. So if the evidence for symmetry is strong, then I think it would be best to say it is due to twin-jet productions of the kind we also discuss in the context of extragalactic nuclei. If there is no evidence for spatial symmetry - and there does not seem to be very much on the basis of the present data -, then each stellar flyby will give you one swath of ejecta.

DISCUSSION OF PAPER BY HO AND TURNER

T.M. Bania: In NGC 4736, is there a difference in spectral index between the central source and the outer ring?

Ho: The core source appears to have a flat spectrum between 2 and 6 cm. The outer ring is very faint, and we have not been able yet to determine its spectral index reliably. It may be thermal, while the central source is nonthermal.

E.M. Berkhuijsen: Why do you think so?

Ho: Preliminary, rough maps suggest that the more compact knots in the ring may be thermal.

Bania: I believe there is an Hα ring surrounding the nucleus of this galaxy with a radius of 1 arcmin.

F.P. Israel: In Sc spirals, the ratio of CO line strength to total radio continuum is almost always higher in the central regions (diameter of order 1') than in the disk. This supports your conclusion about strong star formation in the centres of spiral galaxies.

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Ho: Our study attempts to quantify such statements. We are also pursuing the correlation between thermal radio continuum, CO emission and infrared radiation.

In University garden, at President's reception: (left to right) Hoskin, Higgs, Murray, Davies, Hodge, Elmegreen, Smith, Hilditch, N.N.
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