THE GALACTIC CENTRE

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Abstract. The phenomena displayed by the interstellar medium in the galactic centre are considered. The asymmetries shown by the features between 1 and 3 kpc from the centre together with the presence of material lying out of the galactic plane favour the expulsion hypothesis for their origin. The nuclear disk shows a perturbation which might have resulted from such expulsion. The dense molecular clouds in the disk may well be considered as the most direct evidence that matter is expelled from the nucleus and that this occurs at a high rate. The $+50$ km s^{-1} feature in the direction of Sgr A may be the most recently expelled body of molecular gas. New observations of the central radio source, Sgr A, have revealed details on a very small scale, and the infrared core also shows a complicated structure. Probably a number of individual concentrations of gas and dust are present. While the position of the actual nucleus seems now to have been defined to within a few arcseconds, no indication has yet been found concerning its nature nor concerning the mechanism that enables it to expel the vast expanding masses of gas observed in the central region.

The phenomena displayed by the interstellar medium in the central region of the Galaxy can be roughly divided in the following groups, arranged in order of decreasing distance from the centre.

§	Phenomenon	Gaseous mass ($M_\odot$)	R (pc)	Radial motion (km s^{-1})	Time scale (yr)
I	3-kpc arm	10^7	1000–3000	100	$(5-15)\times10^6$
I	Expanding arm at $+135$ km s^{-1}	10^7			
I	High-velocity features outside galactic plane	10^5			
II	Nuclear disk	4×10^6	800	–	–
III	Expanding molecular clouds	10^6	100–700	200	$(1-2)\times10^6$
IV	Radio sources		0–700		
V	$+50$ km s^{-1} absorption feature	10^5	5–10	50	10^5
VI	Infrared nuclear disk and radio fine structure	10^4	0.5	?	10^3

These data should be considered in conjunction with (1) those on the *stellar* mass density as found from the rotation of the nuclear disk and from the *near*-infrared radiation, which give roughly 10^9 $M_\odot$ within $R=100$ pc, 10^8 $M_\odot$ within 10 pc and 10^7 $M_\odot$ within 1 pc, and (2) the distribution of *far*-infrared radiation (around 100 μm), which shows a central concentration of $38\times15'$, or 110×45 pc, diameter (cf. Borgman, 1974).

I. Features Between 1 and 3 kpc from the Centre

The 3 kpc arm is the best-defined feature. It can be followed from l about 338° to 5° where it merges with low-velocity gas. The part we observe lies in front of the centre. At $l=0°$ its radial velocity is -53 km s^{-1}. In a sector of about 90° galactocentric longitude it has an H I mass of 2×10^7 $M_\odot$.

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The $+135$ km s^{-1} expanding arm lies beyond the centre. It is seen from $l \sim 355°$, where it seems to break off rather suddenly (which suggests that it may at this point be situated within 1 kpc from the centre), to either 12° (according to Simonson and Mader [1973]) or 22° (according to Rougoor's [1964] early study). Its mass is of the same order as that of the 3 kpc arm. Figure 1, taken from a sketch prepared by Rougoor (1964). shows a possible situation of the two arms.

The most important problem in connection with these two features is whether they are caused by gas expelled from the galactic nucleus or whether they are parts of general dynamical phenomena in the Galaxy.

If they are due to explosions from the nucleus very large masses must have been involved. According to the computations by van der Kruit (1971) a mass of between 5 and $10 \times 10^6 M_\odot$ would have had to be thrown out about 12×10^6 yr ago at velocities around 600 km s^{-1} in order to explain the outward motion of the 3 kpc arm. In his model the expulsion took place in two opposite directions, at angles of 25°–30° with the galactic plane. Because of this inclination it might not have completely destroyed

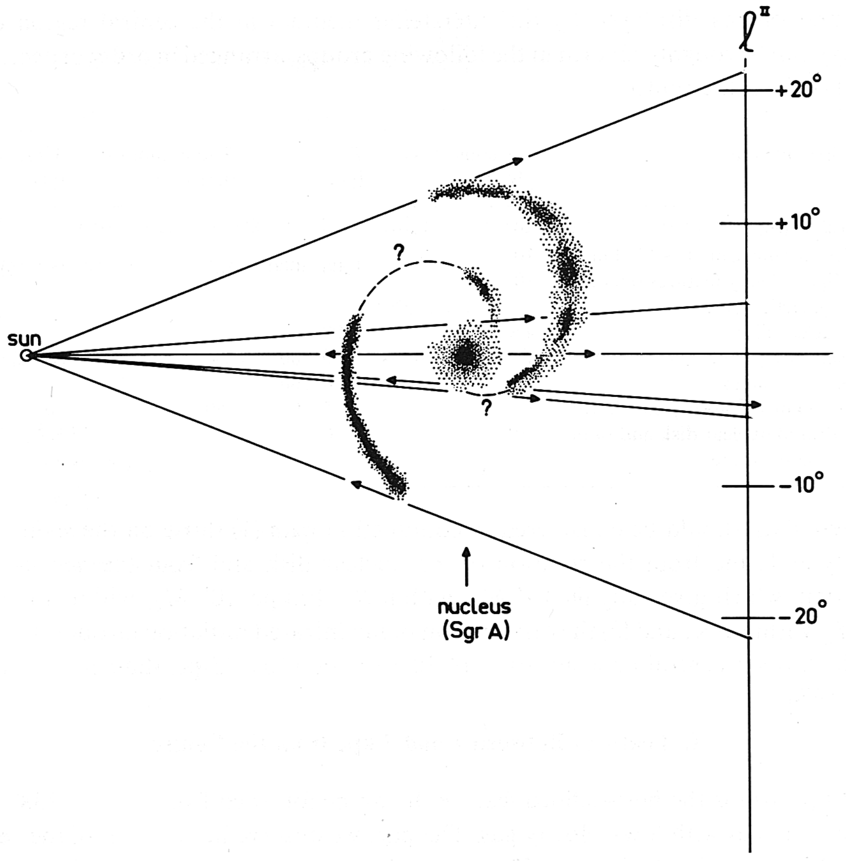

Fig. 1. Schematic sketch of the 3 kpc arm, the expanding arm at $+135$ km s^{-1} and the nuclear disk (from Rougoor, 1964).

the nuclear disk. Sanders and Prendergast (1974) have investigated a model with isotropic expulsion. They suggest that the 3 kpc arm could have gone through an entire epicycle; the expulsion would then have occurred longer ago, and sufficient time might have elapsed to form a new nuclear disk after the earlier disk had been blown away. This model, however, appears to me rather artificial.

Some evidence which appears to support an explosion model, and especially a non-isotropic one, is provided by the existence of large gas complexes in the central region *outside* the galactic plane. These features, originally found by W. W. Shane, were investigated in detail by van der Kruit (1970), and later also by Sanders *et al.* (1972). The observations by the latter authors show a concentration of hydrogen between $-2°$ and $-6°$ latitude and 356° and 8° longitude which at $l=0°$ has a velocity of about -135 km s^{-1}. The total mass is roughly 10^5 $M_\odot$. This is often referred to as van der Kruit's Feature XII. Sanders, Wrixon and Penzias have suggested that it might form part of a 'ring', but the evidence for this is not at all convincing. They have also found some H I features closer to the centre and making large angles with the galactic plane (distances up to a few hundred parsecs, velocities around 200 km s^{-1} and masses of a few times 10^4 $M_\odot$). These various phenomena suggest that gas is being expelled in some favoured directions making considerable angles with the plane. Recent observations at Jodrell Bank which show more detail have fully confirmed this.

EXPULSION OR DISPERSION ORBITS?

The expulsion hypothesis implies that gas masses of the order of 10^7 $M_\odot$ have been thrown out by the galactic nucleus within the last 10 or 15×10^6 yr. Nothing is yet known about the mechanism that could provide the required kinetic energy nor about the origin of this vast quantity of interstellar gas.

It is therefore very important to explore exhaustively other possible explanations of the observed large radial motions.

The possibility that at least some of the expanding features might be parts of a dispersion ring has been studied by Shane (1972), and, in greater detail, by Simonson and Mader (1973). Simonson has reported on this investigation. He concluded that the observations can indeed be interpreted in this manner, and that such an interpretation might be preferred because the alternative requires an ad hoc hypothesis on the nature of the nucleus, while the dispersion orbit can in a plausible way be identified with the inner Lindblad resonance.

There are, however, a number of difficulties in this interpretation. The most serious one is the absence of a proper counterpart of the 3 kpc arm on the other side of the centre. The so-called $+70$ km s^{-1} arm, which has been invoked as a possible candidate, is a weak and uncertain feature, in no way comparable to the 3 kpc arm. It has been suggested that this lack of symmetry might be caused by the action of spiral arms; but then the dispersion ring model loses its simplicity and much of its attractiveness. There is, in the second place, the $+135$ km s^{-1} expanding arm to account for. This lies behind the centre, but can hardly form part of a dispersion ring containing the 3 kpc arm.

Simonson and Mader suggest that it might belong to a second, inner, dispersion ring. However, there is no indication that makes the existence of a second dispersion ring plausible. Moreover, this would again have to be strongly asymmetrical.

Asymmetries such as shown by these two major features seem, on the other hand, to be common in expulsion phenomena. Extreme cases of this are shown by NGC 1275 and M87.

A third difficulty is presented by the phenomena outside the galactic plane, such as van der Kruit's Feature XII. In the dispersion ring model this can only be explained in a rather artificial way.

Finally, it should be remembered that, though we do not understand how matter is expelled from the galactic nucleus, we must in any case accept the expulsion of *some* features, such as the Feature E found by Sanders, Wrixon and Penzias, and the molecular clouds near the centre. The latter contain probably at least a million solar masses. That expulsion *can* take place on a very large scale is moreover demonstrated convincingly by the phenomena in such galaxies as NGC 1275, NGC 4258 and M82.

II. The Nuclear Disk

I now want to discuss briefly the problems around the fast-rotating nuclear disk of about $4 \times 10^6\ M_\odot$ introduced by Rougoor and Oort (1960). I shall not repeat the, in my opinion, very strong arguments that we are indeed observing a rotating disk, and that the velocities observed on the negative-longitude side probably correspond closely to circular velocities in the gravitational field of the Galaxy. There is, however, the problem how the disk could have survived such vast explosions from the nucleus as would be required to explain the radial motions of the expanding arms. A plausible way out of this difficulty is to suppose that the expulsion took place in a strongly anisotropic manner, and at considerable angles with the galactic plane (such as, for instance, in van der Kruit's model), the expelled gas falling back into the general galactic disk at a few kpc from the centre, where it transferred its radial momentum to the disk gas. The inner part of the nuclear disk would, however, still have been seriously perturbed. There are, indeed, clear signs of such a perturbation within about 2° on the positive longitude side, as indicated by Sanders and Wrixon (1972). Due to its rapid and strongly differential rotation the disk might largely recover from disturbances in a period of the order of 10^7 yr.

The distribution of the H I density in the disk has recently been studied by Sanders and Wrixon (1973). It varies from ~ 0.2 cm^{-3} at $R = 600$ pc to ~ 5 cm^{-3} around $R = 100$ pc.

III. The Molecular Clouds

These have been fully described by Robinson (1974). Most, if not all, are moving away from the centre and have therefore probably been expelled from the nucleus. They appear to be confined to a very thin disk, considerably thinner than the H I disk. This is remarkable, especially in view of the fact that much of the H I expulsion seems to occur at large angles with the galactic plane. It may be that the dense molecular clouds originate in some way through an interaction between outgoing streams and the disk.

Dense clouds of molecules are observed from about 358°.5 to nearly +4° longitude. Because no dense clouds have been found below $l = 358°.7$ it is probable that a large fraction lies within 250 pc from the centre. At $l = 0°$ the clouds in front of Sgr A are moving towards us at a velocity of 140 km s^{-1}, and should thus have been expelled during the past one or two million years. The observations of these molecular clouds may well be considered as the most direct evidence that matter is expelled from the galactic nucleus, and that this occurs at a high rate, for the total mass of these clouds must be of the order of 10^6 $M_{\odot}$. The negative-velocity clouds between $l = 358°.8$ and $l = +0°.8$ appear to form a more or less continuous structure which looks like a sector of an expanding ring, such as proposed by Scoville (1972) (cf. Figure 8 in the communication by Robinson). The evidence for a complete ring is, however, unconvincing. The molecular clouds behind the centre are mostly moving at a much lower velocity and are considerably more patchy. In addition, there are large concentrations of dense clouds with positive velocities extending to almost $l = 4°$ which certainly do not fit in with a single ring model. One gets rather the impression that there have been several periods of intensive expulsion, favouring different directions in the disk.

Most of the molecular clouds appear to lie embedded in the disk, However, they have not been stopped in their outward motion by the disk gas, nor carried along by its rotation. In fact, their present column densities are probably so high that they can move practically unimpeded through the disk. Many molecular clouds in the central region show molecular emission for which densities of at least 10^3, in some cases even up to 10^5, H_2 molecules per cubic centimetre are required; with diameters of several parsecs their column densities must be of the order of 10^{22} cm^{-2} or more.

IV. Radio Sources

An interesting phenomenon is the unexplained asymmetry in distribution: The sources north of the centre are mainly thermal, while those south of the centre are nonthermal.

The discrete sources are embedded in a general concentration of thermal as well as nonthermal radiation with a half-intensity diameter of about 300 pc.

The central source, Sgr A, has a very complicated structure, interesting details of which have recently come to light (cf. Figures 3 and 4 of the contribution by Gordon). These data have a very special importance, because they reveal details of nuclear structure which are two orders of magnitude smaller than what can be observed in any other galaxy except M31. The main structure is elongated in an approximately north–south direction, and has variously been called 'component A', or 'Sgr A West'. It contains the centre of the near-infrared concentration of stars as well as the centre of the farther-infrared disk discussed in Section VI. High-resolution observations at 4 cm show pronounced fine structure in the region enclosed by this infrared disk, to which I shall return below. Roughly 1'.7 east of the centre lies a nonthermal component, which has been called Sgr A East, and seems to be the central concentration of a broader distribution. The importance of this component is well brought out in a recent observation with the Fleurs interferometer at 1415 MHz.

V. The $+50$ km s^{-1} Absorption Feature

An intriguing phenomenon connected with Sgr A is the very broad absorption, observed particularly in OH and H_2CO, which is centred at a velocity of roughly $+50$ km s^{-1}. At first sight it looks as though this shows gas flowing into the galactic nucleus. Recent observations with the CalTech interferometer by Whiteoak, Rogstad, and Lockhart, for information on which I am indebted to Whiteoak, show, however, that the formaldehyde absorption at $+50$ km s^{-1} is not at all seen against component A, but mainly against the nonthermal source 1.′7 east of the centre. This makes it possible to interpret the $+50$ km s^{-1} band as caused by gas ejected from the galactic nucleus and seen in absorption against Sgr A east, which may well be centred some 5 pc beyond the nucleus (see Figure 2). The proposed configuration receives

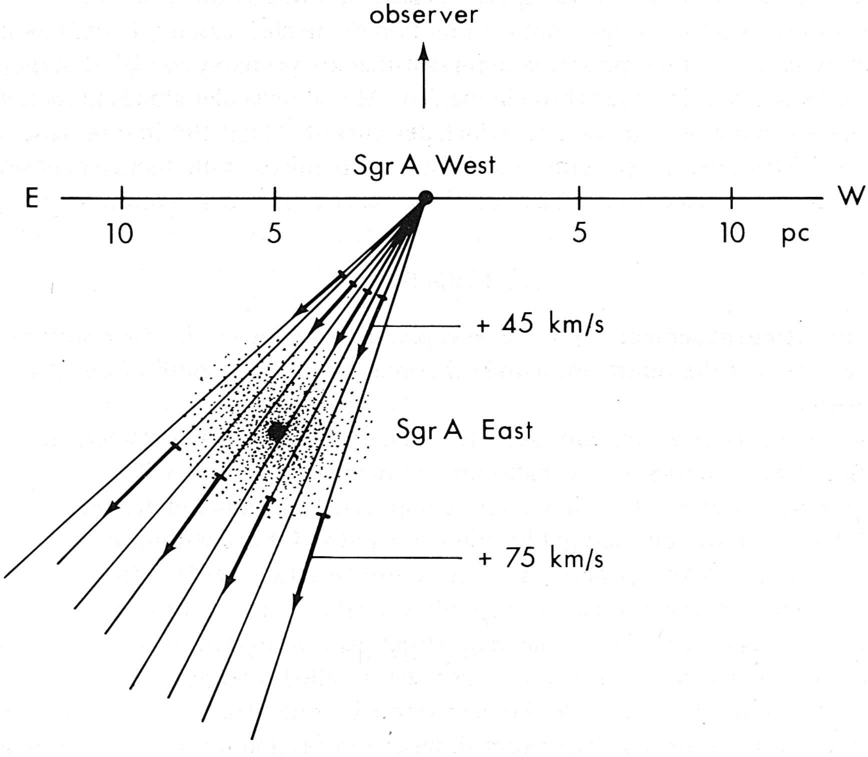

Fig. 2. Possible situation of the gas showing CO emission between $+30$ and $+90$ km s^{-1}, and seen in absorption in the OH and H_2CO absorption lines between $+30$ and $+60$ km s^{-1}.

support from the observations of CO emission around Sgr A. This emission, which is concentrated within 3′ or 4′ (10 pc) from Sgr A, extends over a velocity interval from +30 to +90 km s^{-1}. The formaldehyde absorption, however, takes place only between +30 and +60 km s^{-1}. The higher-velocity gas therefore lies beyond the source against which the formaldehyde is seen in absorption. As shown in the diagrams by Solomon *et al.* (1972), this latter gas is centred some 2′ east of the lower-velocity material. The distribution in space and velocity may therefore be like that drawn in the sketch (Figure 2).

If this interpretation is correct the +50 km s^{-1} feature shows that expulsion of molecular gas has occurred quite recently and may well be continuing at present.

VI. The Infrared Nuclear Disk

Most interesting information on structure near the galactic nucleus has come from the infrared observations. After Becklin and Neugebauer (1968) and others had obtained rather convincing evidence from 2.2 μm observations for a concentration of *stars* at the centre of the Galaxy, and had obtained what appear to be reliable data on the density distribution and total star density from about 0.2 to 50 pc from the centre (cf. Figure 1 of Borgman's review), a remarkable new discovery was made by Rieke and Low (1973). They found that radiation between 4 and 20 μm is concentrated within a circle of about 16″, or 0.8 pc, diameter, which I shall denote by the term 'infrared disk,' or 'infrared core' (Figure 3). Within this disk at least five separate concentrations can be seen. One of these, roughly at the centre, coincides closely with the 'stellar' centre as observed at 2.2 μm and may well be identical with this stellar core. Of the other concentrations one may be an infrared star; the nature of the others is unknown. The close resemblance with the fine structure recently found in the same region at radio wavelengths indicates that they represent individual concentrations rather than fluctuations in the overlying absorption. If they are extended objects their free paths would probably be about equal to the dimension of the disk. The corresponding life times would then be of the order of 10^3 yr.

Radiation and absorption by solid particles must play an important role in the nuclear region. The bulk of the observed radiation is emitted between 75 and 125 μm. Hoffmann *et al.* (1971) have shown that this comes from a source of 38′ × 15′ half-width. Borgman states that it has a total luminosity of 7×10^7 $L_\odot$. The radiation can easily be provided by the central concentration of stars.

VII. The Actual Nucleus

The observations discussed in this session on the galactic centre indicate strongly that the true galactic nucleus lies within the 16″ infrared nuclear disk, probably close to its centre, and coinciding with the radio fine structure observed within Sgr A West. Its position thus seems to be defined to within a few arcseconds. This is an important advance.

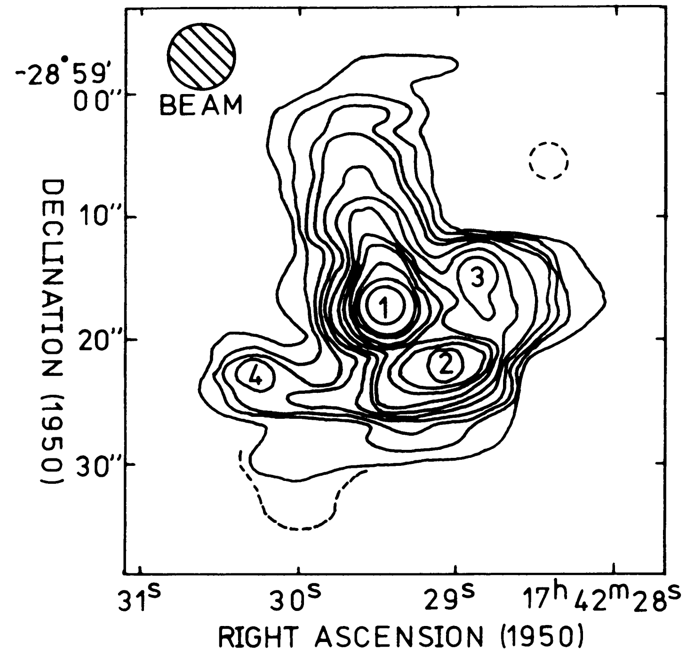

Fig. 3. Distribution of 10.5 μm radiation in the infrared core of the Galaxy (Rieke and Low, 1973).

On the other hand no indication has yet been found concerning its nature, nor concerning the mechanism which enables it to expell the vast expanding masses of gas that are observed in the central region.

As regards the mass of this unknown nucleus the only information we have at present comes from the rotation of the nuclear H I disk. The smallest distance from the centre where its rotation could so far be observed is about 80 pc. From these observations Sanders and Wrixon (1973) have derived an upper limit of 10^8 $M_\odot$ for a point mass in the nucleus. The only way conceivable at present in which one might get dynamical information from regions much closer to the centre is through infrared observations of the distribution and velocities of planetary nebulae, but this appears to be still impracticable with existing instruments.

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DISCUSSION

Robinson: The molecular cannonballs with $n_{H_2} \approx 10^3$ cm^{-3} can clearly travel with ease through the H I nuclear disk with $n_H \leqslant 10$ cm^{-3}. But it is strange that the molecular clouds have such low rotation velocities (≈ 50 km s^{-1}) about the nucleus in the gravitational field that makes the H I disk rotate at 250 km s^{-1}. The molecular clouds have insufficient velocity to escape from the nucleus and insufficient angular momentum to maintain their present radii. They must soon spiral back towards the nucleus.

In Oort's summary he has shown a total mass of only 10^6 $M_\odot$ for the molecular clouds near the galactic center. However, Kaifu has computed 10^8 to 10^9 $M_\odot$ for the ring from H_2CO/CO observations. Oort's mass of 10^6 $M_\odot$ looks much too small – just the molecular cloud associated with Sgr B2 is believed to have a mass of at least 5×10^5 $M_\odot$.

Palmer: While the estimates of densities and consequently masses of molecular clouds are the best we can make at the present time, Oort is certainly correct in being conservative in his mass estimates. Effects such as radiative transfer in the cloud and possible unresolved structure have usually not been properly taken into account to date. When these are worked out in detail, the mass estimates may be reduced.

Menon: If such molecular clouds exist so close to the nuclei of galaxies, should we not expect to find early type stars in the nuclei of galaxies?

Mezger: Observations of H II regions suggest the highest rate of O star formation encountered in our Galaxy is within 100 pc from the center.

Oort: As the time scale for the molecular clouds near the center is only of the order of 10^6 yr, stars may not have had time to form. But Mezger is, of course, right in pointing out that the H II regions like that found in Sgr B2 show that OB stars must have formed. This would be possible even in the short time indicated above if the gas density is quite high.

Menon: I would just like to ask, do we *see* OB stars in the nuclei of other galaxies?

Robinson: In this regard also, the nucleus of NGC 253 is similar to that of our Galaxy. The nucleus of NGC 253 is not like that of M31 but consists of a number of giant H II regions.

Oort: And there are other galaxies like this as well.

Swarup: In your model of expulsion of the $+50$ km s^{-1} cloud from the galactic nucleus, would there not exist serious difficulties of formation of molecules at the nucleus?

Oort: One does not know the mechanism by which the clouds are expelled. It might either be such that molecules would not be destroyed or else the densities might be so high that they would have been formed in a very short time after the expulsion.

Simonson: Leaving aside the nucleus itself, the largest source of kinetic energy in the Galaxy is rotation. We have merely tried to tap a small fraction of this energy to trap the gas into resonant orbits.