Shocked molecular hydrogen emission from the centre of the Galaxy

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Summary. Observations of molecular hydrogen emission lines near 2 \( \mu \)m show that the nucleus of the Galaxy is encircled by a ring of shocked gas; this ring has a radius of 2 parsecs, lies in the plane of the Galaxy, is symmetric about the centre of mass, and rotates in the sense of Galactic rotation. Gas is being shocked at a rate of \( > 10^{-2} M_\odot \text{yr}^{-1} \), to a temperature about 2000 K, in a region of mean molecular density \( 5 \times 10^3 \text{cm}^{-3} \). The momentum needed to shock the gas cannot be provided radiatively. Mass loss from the nucleus can account naturally for the central density minimum and for the shocked gas; a mass loss rate of \( 3 \times 10^{-3} M_\odot \text{yr}^{-1} \) is required. Simple time-scale arguments suggest that observable molecular hydrogen emission from the Galactic centre may be a long-lived phenomenon. A model involving a single central engine is suggested.

1 Introduction

The interstellar density distribution in the central 10 parsec of the Galaxy has been determined by radio and infrared observations (Brown, Johnson & Lo 1981; Lacy et al. 1980; Becklin, Gatley & Werner 1982, hereafter BGW) and can briefly be described as follows. The interstellar material is confined chiefly to the plane of the Galaxy. Within 2 parsec of the centre the density is generally very low; the gas is ionized and occurs in high density clumps (\( n_e \sim 10^5 \text{cm}^{-3} \)) which fill a few per cent of the volume. Beyond 2 parsec the density in the
plane rises abruptly, and the gas is neutral. The origins of this density distribution are presently not well understood (Gatley 1984).

In this paper we present observations designed to test the hypothesis that the central density minimum is a mass loss bubble generated by a wind from the object or objects responsible both for the ionization of the gas and for the high luminosity \((L \gtrsim 10^7 L_\odot)\) of the central parsec (BGW). Constraints on the origins of this luminosity are urgently needed to distinguish between a plethora of models, which presently range from 'normal' star formation to black holes (Gatley & Becklin 1981, and references therein).

2 Observations

Fig. 1 shows a 6-cm map of the free–free emission from the Galactic centre measured with the VLA (Brown et al. 1981). Superposed on this map are the positions at which molecular hydrogen line spectra were measured; the positions are labelled according to their location either north-east or south-west of the centre by an arbitrary alphabetic label A through E.

The first observation of the \(V = 1 \rightarrow 0 S(1)\) line at 2.122 \(\mu\)m was obtained with the United Kingdom Infrared Telescope (UKIRT) at Mauna Kea, Hawaii in 1982 May using a circular variable filter wheel (CVF) of 1 per cent spectral resolution with a solid nitrogen cooled InSb detector system having 12 arcsec diameter field of view. The separation between

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Figure 1. Contours of 6-cm emission (Brown, Johnston & Lo 1981) with the positions at which molecular hydrogen spectra were obtained superposed.
the beam positions produced by the telescope chopping secondary mirror was 120 arcsec east–west, and a spectrum was measured at the single spatial position SW A (Fig. 1). Measurements were made through the wavelength range 2.05–2.21 μm in increments of 5 × 10⁻³ μm, that is, every quarter of a resolution element.

Subsequently, measurements were made at Mount Stromlo Observatory, (MSO) Australia, using the 1.9-m telescope. The MSO cooled grating spectrometer (Jones et al. 1982) has a spectral resolution of 0.2 per cent when used with a 13.6 arcsec square field of view. A 50 arcsec east–west beam spacing was employed. Wavelength calibration was established by observations of H I Bγ in X Oph and O Aqr, and intensity calibration by observations of γ Sgr. Spectra were taken about the wavelength of the V = 1 → 0 S(1) line (2.122 μm) at the eight positions shown in Fig. 1, and a single spectrum including both the V = 2 → 1 S(1) line (2.248 μm) and V = 1 → 0 S(0) line (2.223 μm) was measured at the position SW A.

3 Results

3.1 Analysis of Spectra

(1) Fig. 2 shows the UKIRT CVF spectrum of position SW A. The V = 1 → 0 S(1) line is clearly detected; this is the first detection of molecular hydrogen emission from the Galactic centre.

(2) Fig. 3 shows the higher spectral resolution MSO spectra of the V = 1 → 0 S(1) line obtained at the eight positions indicated in Fig. 1. The molecular hydrogen line is clearly seen at most positions, most strongly at SW A and NEB. Comparison of the strengths of the V = 1 → 0 S(1) and V = 2 → 1 S(1) lines (Fig. 4) at position SW A shows that the V = 1 → 0 line is stronger by about an order of magnitude. This result precludes the possibility that the molecular gas is excited by ultraviolet fluorescence, and shows that the gas is shocked to a temperature about 2000 K (Beckwith, Persson and Neugebauer 1979).

(3) Fig. 5 shows the strength of the V = 1 → 0 S(1) line as a function of position from the infrared source IRS 16, which is believed to lie at the very nucleus of the Galaxy (Becklin & Neugebauer 1975). The position of IRS 16 is indicated in Fig. 1. The striking result is that the strength of the molecular hydrogen emission peaks sharply at a radius of 40 arcsec (1.7 parsec at a distance of 8.7 kpc) from the nucleus. The simplest interpretation of this result is that the shocked gas forms a ring around the centre of the Galaxy. Analysis of far
Figure 3. CGS spectra of the H$_2$ $V = 1 \rightarrow 0$ S(1) line taken at the eight positions indicated in Fig. 1. Typical error bars (1σ) are shown in each frame.
Figure 4. CGS spectrum of position SW A including the wavelengths of two $H_2$ lines, $V = 1 \rightarrow 0 S(0)$ at 2.223 $\mu$m and $V = 2 \rightarrow 1 S(1)$ at 2.248 $\mu$m.

Figure 5. The measured strength of the $V = 1 \rightarrow 0 S91)$ line as a function of distance from IRS16.

infrared ($\sim 100 \mu$m) photometry has shown previously that there is a ring of neutral material at this radius (BGW).

(4) The data of Fig. 3 are of sufficient spectral resolution to show marginal evidence of velocity variations between different spatial positions. The data are summarized in Table 1. For the most part velocities relative to the Local Standard of Rest are positive in the north-east and negative in the south-west; this is consistent with Galactic rotation. In particular the velocity shift between positions NEB and SW A is $\sim 260$ km s$^{-1}$. If the molecular emission arises from a thin ring of radius 1.7 pc rotating at 130 km s$^{-1}$ in gravitational equilibrium, then the implied interior mass is $\sim 6.5 \times 10^6 M_\odot$, in reasonable agreement with other estimates (Becklin & Neugebauer 1968; Sanders & Lowinger 1972; Lacy et al. 1980; Genzel et al. 1984; Allen, Hyland & Jones 1983).

3.2 Derived Parameters

(1) Because of the meagre spatial coverage of the present observations it is necessary to make some assumptions about the geometry of the shocked region in order to proceed with the analysis. We assume that the shocked gas is distributed axisymmetrically about the nucleus of the Galaxy, that the radius of this shocked region is 1.7 pc in the plane, that the radial extent of the shocked region is less than the experimental beamsize (i.e. $< 0.6$ pc; this
Table 1.

<table>
<thead>
<tr>
<th>H₂ line</th>
<th>Position θ (arcsec)</th>
<th>Name</th>
<th>R (10⁻²⁰ W cm⁻²)</th>
<th>Velocity (km s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v = 1 + 0 S(1) (2.122μm)</td>
<td>32S 20W</td>
<td>SW A</td>
<td>38</td>
<td>5.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>26S 20W</td>
<td>SW B</td>
<td>32</td>
<td>3.4 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>26S 11W</td>
<td>SW C</td>
<td>25</td>
<td>0.0 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>32N 20E</td>
<td>NE A</td>
<td>38</td>
<td>1.8 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>38N 20E</td>
<td>NE B</td>
<td>43</td>
<td>5.0 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>28N 16E</td>
<td>NE C</td>
<td>32</td>
<td>1.9 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>23N 11E</td>
<td>NE D</td>
<td>25</td>
<td>1.0 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>41N 29E</td>
<td>NE E</td>
<td>50</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td>v = 1 + 0 S(0) (2.223μm)</td>
<td>32S 20W</td>
<td>SW A</td>
<td>38</td>
<td>1.2 ± 0.3</td>
</tr>
</tbody>
</table>

a Relative to IRS 16.
b Distance from IRS 16.
c Relative to Local Standard of Rest, assuming rest wavelengths given by Gautier et al. (1976).

point is discussed further below), and that the shocked region is at least as extended as the beamsize orthogonal to the Galactic plane (i.e. z > 0.6 pc).

Equivalently we assume that we have observed a complete ring of shocked gas surrounding the nucleus in the plane, which subtends Ω/4π ~ 10 per cent at the nucleus, and that 22 per cent of the azimuthal extent is within the experimental beam at positions SW A and NE B. Clearly, further observations will readily elucidate the true geometry; the assumption that the emitting region is extended orthogonal to the Galactic plane is probably rather secure, for the far infrared observations of BGW suggest Ω/4π ~ 0.5 for the dense neutral material at the radius of the shocked emission. Therefore our observations provide only lower limits on the mass and spatial extent of the shocked region, and our assumed 'ring of emission' is in all probability only a section of a larger structure.

(2) The observed strength of the V = 1 → 0 S(1) line at positions SW A and NE B (the limbs of the ring of emission) is 5 × 10⁻²⁰ W cm⁻². As described above, we assume that this is the emission from 22 per cent of the whole ring. The extinction to the Galactic centre at 2.1 μm is 2.5 mag (Becklin & Neugebauer 1968; Becklin et al. 1978). Therefore the de-reddened line strength for the whole ring is 2.3 × 10⁻¹⁸ W cm⁻², which corresponds to 50 Lₒ in this line alone. The luminosity in all the molecular hydrogen lines is therefore about 500 Lₒ (Beckwith 1981).

(3) The A-value for the V = 1 → 0 S(1) line is 3.5 × 10⁻⁷ sec⁻¹ (Turner, Kirby-Docken & Dalgarno 1977), and is similar for most of the other important H₂ emission lines. The mass of shocked gas required to produce 500 Lₒ in H₂ emission lines is ~ 1.2 × 10⁻² Mₒ. The cooling time for this shocked gas is of order one year (Beckwith 1981), and the shock velocity is likely to be in the range 10–24 km s⁻¹ (Kwan 1977). Therefore, the preshock density is of the order of 5 × 10³ molecules cm⁻³, and the thickness of the shocked layer normal to the shock is ~ 6.3 × 10⁻¹⁳ cm.

(4) The force required to drive a 20 km s⁻¹ shock through 1.2 × 10⁻² Mₒ of gas per year is 1.4 × 10³ dynes. The luminosity of the central parsec of the Galaxy is < 4 × 10⁷ Lₒ (BGW) of
which about 10 per cent falls on the shocked ring. Therefore a force of \( < 5 \times 10^{29} \) dynes is provided radiatively, and luminosity is insufficient to drive the shock. This point is discussed further in Section 3.3 below.

(5) Mass loss provides a viable mechanism to drive the shock. Observations of the He I 2.06 \( \mu \)m line at IRS 16 show emission at velocities out to \( \pm 750 \) km s\(^{-1}\) (Hall, Kleinmann and Scoville 1981). If a wind at 750 km s\(^{-1}\) impinges on the shocked region then a mass of \( 3 \times 10^{-4} M_\odot \) yr\(^{-1}\) must be deposited in order to sustain the shock. Therefore an isotropic wind of \( M \sim 3 \times 10^{-2} M_\odot \) yr\(^{-1}\) at 750 km s\(^{-1}\) from IRS 16 can drive the shock.

(6) The mechanical energy present in such a mass loss flow is \( 1.3 \times 10^8 L_\odot \). This is far greater than the luminosity of the molecular hydrogen emission, and so mass loss can indeed power the observed \( H_2 \) emission. It is interesting to note, however, that the energy in the mass loss flow is insufficient to excite the observed quantity of ionized gas in the central parsec (Lacy et al. 1979). As has been previously argued, this gas is probably ionized radiatively (Lacy, Townes & Hollenbach 1982).

(7) Observations of mass loss rates from O stars have shown that there is a luminosity — mass loss relationship with wide applicability (Garmany et al. 1981; Abbott, Bieging & Churchwell 1981) which is consistent with theories of radiatively driven stellar winds (Castor, Abbot and Klein 1975). Extrapolation of this relationship into the regime of high luminosity and mass loss appropriate to the Galactic nucleus gives the interesting result that a mass loss rate of \( 3 \times 10^{-3} M_\odot \) yr\(^{-1}\) arises from a single object of luminosity \( 4 \times 10^7 L_\odot \). On the other hand, the mass loss rate expected from a cluster of young stars hypothetically consistent with observations of the ionized gas would be less than \( 10^{-4} M_\odot \) yr\(^{-1}\) (Lacy 1981; Lacy et al. 1982). Therefore the mass loss rate deduced here lends support to the idea that there is a central engine in the nucleus of the Milky Way.

### 3.3 Comparison with Other Observations

The fact that the density of neutral gas in the Galactic plane rises abruptly beyond 2 parsec from the centre has been demonstrated previously both by far infrared (25–150 \( \mu \)m) continuum studies (BGW) and by observations of the \( ^3P_1-^3P_0 \) 63 \( \mu \)m fine structure line of neutral atomic oxygen (Lester et al. 1981; Genzel et al. 1982; Genzel et al. 1984). The far infrared continuum is thermal emission from dust. The observations show that most of the luminosity of the central parsec escapes as optical and ultraviolet radiation because the interstellar dust density is very low, but this power is absorbed in the higher density region beyond 2 parsec radius. The size of the far infrared emitting region (in which this power is absorbed) is therefore an indicator of the interstellar density, for this region has an absorption optical depth \( A_V \sim 1 \). Given a normal gas to dust ratio, the observed size suggests a gas density \( \sim 10^{-3.5} \) cm\(^{-3}\) in the high density region (BGW; Gatley et al. 1977), in fair agreement with the value of \( 5 \times 10^{-3} \) cm\(^{-3}\) deduced from the present observations. The size of the far infrared emitting region is, however, very much larger than the shocked molecular hydrogen emitting region; the total mass implied by the continuum observations is \( \geq 10^3 M_\odot \) but the shocked mass is \( \sim 10^{-2} M_\odot \).

The neutral oxygen emission is very spatially extended, and is clearly correlated with the far infrared continuum. The radial extent of the oxygen emission is \( \sim 4 \) pc (Genzel et al. 1984), which is very much greater than the 2.2 \( \times \) 10\(^{-6}\) pc derived here for the radial extent of the shocked gas. Presumably the oxygen is excited in the volume in which the high luminosity of the nucleus is deposited, and this is why the oxygen and far infrared continuum emission correlate. Therefore the oxygen emission is not excited by the mass loss which shocks the molecular hydrogen. This conclusion has also been reached by Genzel et al. (1984).
A simple picture therefore emerges, in which both the mass loss and the high luminosity of the nucleus strongly influence the appearance of the interstellar medium in the central 10 parsec of the Galaxy. The mass loss creates a central density minimum, 'a mass-loss bubble' (cf. Castor, McCray and Weaver 1975) and shocks the higher density exterior material in a thin sheet. The radiation propagates well beyond the shocked gas, into a region $A_V \sim 1$ thick, where it is absorbed by dust. Gas within the mass-loss bubble is ionized by ultraviolet radiation from the nucleus; the distribution of this gas is clumpy (Lacy et al. 1980) and the clumpiness probably results from the fact that this gas is located within the mass-loss flow.

4 Discussion

The symmetry of the observed molecular hydrogen emission about the Galactic nucleus suggests immediately that the excitation of the gas is intimately connected with the nucleus itself. The observed ratio of the $V = 2 \rightarrow 1$ and $V = 1 \rightarrow 0.S(1)$ lines shows that the gas is shocked, but the luminosity of the nucleus (BGW) is insufficient to drive the shock by radiation pressure. The simplest explanation for the $H_2$ emission is that we are observing a mass loss bubble created by mass outflow from the nucleus. Spectroscopy of the nuclear source IRS 16 shows evidence for outflow at velocities up to 750 km s$^{-1}$ (Hall et al. 1982); an isotropic mass loss rate of $3 \times 10^{-3} M_\odot$ yr$^{-1}$ at this velocity can account for the observed molecular emission. Thus the observed luminosity and mass loss rate of the Galactic nucleus are found approximately to satisfy a relationship for mass loss versus luminosity established from observations of individual early type stars (Garmany et al. 1981; Abbott et al. 1981). This result argues against models in which the bulk of the nuclear luminosity is attributed to a cluster of young stars (Rieke & Lebofsky 1981, and references therein) and supports instead the notion that there is a single central engine in the Galactic nucleus.

For the remainder of this paper we therefore adopt the hypothesis that there is a single central engine in the nucleus of the Galaxy, and proceed to discuss constraints on the nature of this object, its impact on the local interstellar medium, and the possible evolution of the nuclear region. This discussion will necessarily be speculative.

5 Speculation

The far infrared continuum and neutral oxygen observations (Section 3.3) indicate that there is $\gtrsim 10^3 M_\odot$ of neutral gas present, of which only about $10^{-2} M_\odot$ is shocked per yr. Therefore, even without any replenishment, the molecular hydrogen emission might last $10^5$ yr. The giant stars in the central 10 parsec of the Galaxy alone will, however, return in excess of $10^3 M_\odot$ yr$^{-1}$ of material to the interstellar medium. There is no reason to assume that the emission of detectable molecular hydrogen emission is a short-lived phenomenon: it is likely to occur throughout the duration of nuclear mass loss. The possibility of transient phenomena, such as supernovae, has, however, been raised (e.g. Brown 1982) in the discussion of the Galactic centre, chiefly because of the presence of a central density minimum. We prefer the hypothesis that this density minimum is a consequence of nuclear mass loss, and that the mass loss is a consequence of the high luminosity of the central engine (Castor et al. 1975).

The analysis given in Section 3 assumes both that the molecular emission is axisymmetric and that the mass loss is isotropic. But, in the interpretation of the radio observations of the plasma interior to the molecular ring (Brown 1982; Ekers et al. 1983), asymmetric structures
such as jets and spirals have been mooted. With regard to the jet hypothesis, the molecular hydrogen emission from the north-east, especially position NE B, is particularly interesting, because it originates from a region devoid of free–free emission (Fig. 1) beyond the point of impact of a ‘jet’. In the present picture, this region is impacted by the nuclear mass loss but is not irradiated by ionizing radiation. The ionizing radiation emitted towards this direction from the nucleus must therefore be absorbed by intervening gas located within the central density minimum; this gas must shield the molecular ring very effectively. Previous conclusions (e.g. Lacy et al. 1980) are at odds with this result; specifically, it has been suggested that the plasma is so clumpy that only a modest fraction of the nuclear radiation is intercepted. The origins of this analysis lie in the fact that each position of enhanced plasma emission (that is, each ‘clump’) has a well-defined velocity (Lacy et al. 1980). Accordingly we suggest a modification to this interpretation consistent with the observational situation: the plasma may be distributed in ‘streamers’, that is, long thin sheets of material stretching appreciable distances in circumference around the nucleus. Such structures would appear limb brightened and would have a well defined velocity, satisfying the requirements of the plasma observations, yet would subtend large angles at the nucleus, satisfying the requirements of the present observations.

In a thorough discussion of the alternatives, Ekers et al. (1983) conclude that ‘the tidal distortion of infalling material seems to provide the most coherent explanation of the observed phenomena.’ Thus, infall of material might be the origin of these plasma ‘streamers’ and may be related to the presence of nuclear mass loss in the following way. Each year the mass loss flow deposits $3 \times 10^{-4} M_\odot$ of material into the molecular ring. But this material has no angular momentum, and so mass may flow back inwards at a similar rate. The free fall time from 1.7 pc is $\sim 10^4$ yr, and so we expect to find some $3 M_\odot$ of material, at a minimum, within the low density interior of the mass-loss bubble. This is comparable to the observed mass of plasma. Also, normal mass loss from late type giants in the central few parsec of the Galaxy will also be contributing mass to this flow. Since this infalling material is within the mass loss wind, the prerequisites for instabilities are likely to be present. We tentatively identify this infalling material as the plasma streamers. In this model the plasma should be chiefly located in the Galactic plane, and should rotate in the sense of Galactic rotation. Both of these phenomena are observed (Lacy et al. 1980); neither is predicted by models involving outflow alone. A different, but perhaps relevant combination of mass loss and accretion, with filamentary instabilities in the accretion flow, has been considered by Dopita (1981) for mass loss bubbles within molecular clouds.

The fate of this infalling material is uncertain; it may fuel the central engine by accretion, be swept outwards again in the mass loss process, or form stars. Before discussing accretion, we mention in passing that star formation in the central parsec might, in fact, proceed without observable consequences: suppose that the infalling mass ($3 \times 10^{-4} M_\odot$ yr$^{-1}$) plus the accumulated mass loss from giant stars in the central 1.7 parsec ($\sim 5 \times 10^{-4} M_\odot$ yr$^{-1}$) is efficiently used in star formation with a normal IMF having a minimum stellar mass of 0.2 $M_\odot$. Then the mean number of ionizing photons produced by the early type stars thus formed is much less than 10 per cent of that required to maintain the current level of ionization (Lacy 1981). Therefore the central engine can dominate the excitation of the Galactic centre even in the presence of star formation. This conclusion underlines the fact that star formation models of the Galactic centre invariably find that a normal IMF is inconsistent with observation (Rieke & Lebofsky 1981; Lacy et al. 1982).

Thus the construction of the star formation models proceeds on an arbitrary basis, and, although not implausible in principle, such models are not demanded by observation; in fact the high mass loss rate deduced here is more supportive of the notion of a single central
source. Therefore, in the context of 'star formation' models, it may be more appropriate to
analogize with single, very luminous, objects such as R136 in the Large Magellanic Cloud
(Cassinelli, Mathis and Savage 1981). Both the luminosity and the mass loss rate of R136 are
similar to the values found here for the Galactic nucleus.

An attractive alternative to star formation is provided, however, by models involving
accretion onto a massive central object. We have argued that the observations indicate accre-
tion is actually taking place, and that there is a central engine; further arguments in favour of
accretion models are available, as follows. First, there is considerable evidence that violent
explosive events centred on the nucleus have occurred in the past (Oort 1977), and that such
events sweep out interstellar material on very large scale sizes of hundreds to thousands of
parsecs. Secondly, positron annihilation radiation is observed from the direction of the
Galactic centre; the likely source of positrons is photon–photon collisions in the vicinity of
a compact object (Lingenfelter & Ramaty 1982). Thirdly, since accretion models are clearly
appropriate for the nuclei of at least some external galaxies it is necessary to consider this
possibility seriously for the nucleus of our Galaxy (Gatley & Becklin 1981).

If we adopt the hypothesis that an explosive event several million years ago swept out
virtually all the interstellar material (Güsten & Downes 1980), turning off the central engine
by stopping the accretion, then two consequences emerge. First, the current modest level of
activity is attributable to the present accretion rate, which can plausibly be larger at other
epochs. Secondly, the $10^3 M_\odot$ of neutral material within the central few parsec must have
accumulated in a few million yr: as shown above, the mass loss rate from giant stars will
account for just this amount of material. Many possible causes of increased accretion can
easily be postulated, leading in this picture to a sudden increase in nuclear activity. These
include infall of stars or molecular clouds, possibly triggered by galaxy interactions (cf.
Hutchings & Campbell 1983). We find it significant, however, that it is possible at this time
to model the interstellar material simply as the accumulated mass lost by giant stars since the
last phase of nuclear activity. Therefore we conclude that the molecules detected in this
experiment have formed locally in the Galactic centre, and we predict that observable
molecular emission will continue until the next outburst. It is interesting to note that a
bright extragalactic source of molecular hydrogen emission is the nucleus of NGC 1068
(Thompson, Lebofsky and Rieke 1978; Hall et al. 1981), and that the shocked mass there is
enormously greater than that deduced here.

Speculative as this line of argument is, we find the case for the existence of a central
engine in the nucleus of the Galaxy to be both viable and attractive.

6 Conclusions

(1) The nucleus of the Galaxy is encircled by a thin ring of hot shocked molecular gas.

(2) An isotropic mass loss rate of about $3 \times 10^{-3} M_\odot$ yr$^{-1}$ from a single central object is the
most attractive mechanism by which to form and shock this ring.

(3) This mass loss rate can be driven by a single luminosity source of approximately
$4 \times 10^7 L_\odot$. We identify this source as IRS 16.

(4) We speculate that the interstellar material in the inner Galaxy is the accumulated mass
lost from giant stars since the time of the last nuclear outburst, that the observed molecules
have formed in situ, and that the plasma in Sgr A is infalling.

(5) Accretion onto a central massive object, possibly a black hole, is the most attractive
mechanism for the nuclear source. The accretion process is a quasi-steady state phenomenon,
currently resulting in a low level of activity, but capable of periodic outburst.
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