ON HEATING, IONIZATION, AND STAR FORMATION IN THE GALACTIC CENTER REGION

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ABSTRACT. The ionization of interstellar gas and the heating of dust near the galactic center are usually assumed to be dominated overall by the radiation emanating from young, massive stars. This paper questions that assumption by pointing to the paucity of direct evidence for current star formation and by considering alternative sources of ionization and luminosity. It is suggested that star formation can be inhibited by the strong, poloidal magnetic fields observed in the galactic center. The presence of some red supergiants (e.g., IRS7) can be understood if massive star formation occurs episodically.

1. Introduction

The finding that a significant portion of the radio emission from the inner few degrees of the Galaxy is either clearly nonthermal or is associated with magnetic structures such as the Arc or the radio threads has led to the notion that there are radio emission mechanisms in this region other than those resulting from ionization by OB stars, and thus that star formation there may be relatively less important -- even inhibited -- relative to the galactic disk (Morris *et al.* 1983).

The evidence is fairly clear that stars <u>have</u> formed within the past 10^8 yrs in the galactic center (Sellgren, these proceedings). Furthermore, there is indisputable evidence for current star formation activity in or near the cores of substantial clouds near the galactic center: Sgr B2, Sgr B1 (G0.5-0.0), and Sgr C. Indirect evidence for star formation has been marshalled by Mezger and Pauls (1979), Güsten (this volume), and Cox and Laureijs (this volume). These authors show that the total ionizing flux implied by the radio continuum emission and the total infrared luminosity are consistent with a normal rate of star formation per unit mass of molecular gas in the galactic center (hereafter GC) region. However, in the entire reservoir of 10^8 $M_\odot$ of molecular gas in the inner 500 pc (Güsten, this volume), there are no direct indicators that stars are currently forming at a rate comparable to that in the disk.

Here, I present arguments supporting the view that star formation is currently suppressed in the galactic center, and thus that the global indicators -- thermal radio flux and infrared luminosity -- may be enhanced by mechanisms other than those associated with star formation. Since it cannot yet be demonstrated unequivocally that star formation is either normal or suppressed near the galactic nucleus, one must proceed cautiously when interpreting phenomena there in terms of a presumed population of OB stars.

M. Morris (ed.), The Center of the Galaxy, 171–177.

2. Masers

Masers in molecular clouds, particularly H_2O masers, have proven to be direct indicators of protostellar condensations, so they permit an assessment of the ubiquity of star formation. On the basis of observations of masers in the disk, and given the relative quantity of gas in the galactic center, one might expect to be able to detect a few hundred masers there. However, surveys for OH and H_2O masers have revealed very few near the galactic center (fig. 1), and some of these are merely superimposed along the line of sight. Güsten and Downes (1981) offer various possibilities to account for the curious absence of masers, including a differing initial mass function in the galactic center, and tidal disruption of maser cloudlets. Another possible explanation is that the enhanced metallicity of the galactic center has a negative effect on the maser pump. Of course, one of the most straightforward explanations is that there is relatively less star formation taking place there. The significance of masers can be better assessed when more complete and more sensitive maser emission surveys are made of the inner Galaxy and compared with a control region of the disk. Such observations are apparently under way, so new information on masers may be available soon.

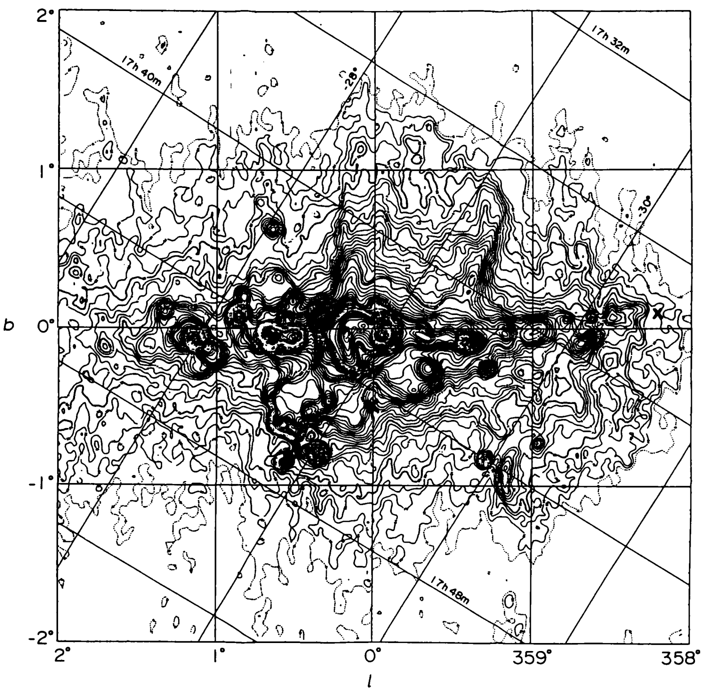

Figure 1: Locations of known H_2O and OH masers within the inner few degrees of the Galaxy, superimposed upon the 10.5-GHz radio continuum map of Sofue *et al.* 1984. Filled circles indicate the positions of H_2O masers (from Güsten and Downes 1983; Caswell *et al.* 1983; Knapp and Morris 1976; Morris 1976), while crosses signify the locations of known OH masers (Caswell and Haynes 1983).

3. Alternative Sources of Ionization and Luminosity

The use of global infrared and radio luminosities to infer star formation rates presupposes an OB star origin for both. But there are alternative sources of both energy and ionizing radiation, so this method should be approached with caution. Obviously, some of the radio emission emanating from the inner Galaxy is nonthermal (Yusef-Zadeh, this volume). Reich *et al.* (1987) have separated the thermal and nonthermal components of GC radio emission by comparing the large-scale radio and infrared images. Removal of the non-thermal component, however, still leaves a thermal flux which requires $\sim 10^{52}$ Lyman continuum photons if it is to be explained entirely by photoionization (Güsten, this volume). We emphasize that sources for such a flux have not yet been identified, except in a few localized sources of radio emission, so we consider here what some of the alternatives to photoionization by hot, young stars might be. None of the alternatives is hypothesized to be globally preferable to the standard picture based on current formation of massive stars, but they should be considered at least as potential contributors.

3.1 COLLISIONAL IONIZATION

Given the large, non-circular motions of many clouds in the GC, it seems likely that some of the ionization is collisional rather than radiative. Clouds colliding with relative velocity exceeding about 50 km s^{-1} can produce ionizing shocks, depending on the magnetic field strength and configuration. In addition, clouds moving at such speeds against the strong magnetic field hypothesized in the inner 50 pc of the Galaxy (see below) can have their surface layers ionized by the Alfvén critical ionization velocity phenomenon. Morris and Yusef-Zadeh (1989) invoked this collisional ionization mechanism to account for the arched radio filaments -- sheets or channels of ionized gas lying within or at the surface of a cloud having a large peculiar velocity (see Yusef-Zadeh, this volume).

Yet another collisional mechanism is possible if currents are driven through interstellar matter by a unipolar induction mechanism, again as a result of the large peculiar velocities of clouds with respect to the magnetic field lines in the GC (Benford, this volume; Morris and Yusef-Zadeh 1989). Then, the ionization might occur by electron impact in regions where the density is low enough to permit some fraction of the electrons to be accelerated to 13.6 eV before suffering a collision.

So, while the operation of a collisional ionization mechanism is not yet proven (for example, Genzel *et al.*, in this volume, argue that the arched filaments are photoionized), it is worthy of further investigation. However, even if it can be conclusively demonstrated to occur at some location, it is difficult to assess its importance for the overall ionization budget of the GC.

3.2 LUMINOSITY OF BULGE AND OLD DISK POPULATION STARS

The luminosity density of old stars in the GC (primarily from K and M giants) is determined by IR observations to be about 1.5×10^5 $L_\odot$ pc^{-3} $r(pc)^{-1.8}$. This luminosity will be absorbed by dust and reradiated in the far-IR, so it should not be neglected in the accounting of luminous energy. For example, the -30 km s^{-1} molecular cloud associated with the arched radio filaments lies about 25 pc in projection from the nucleus, and has projected dimensions of about 30 by 15 pc (Serabyn and Güsten 1987). Adopting a mean depth of 10 pc, and assuming that the cloud is at its projected distance, one finds the stellar luminosity contained and absorbed within the cloud to be $2 \times 10^6\ L_\odot$. If absorption at the cloud surface of starlight originating outside the cloud is also considered, it appears that the far-IR luminosity resulting from evolved stars is a large fraction of the $10^7\ L_\odot$ observed from this cloud (see Morris and Yusef-Zadeh 1989). Most of the clouds within 50 pc of the nucleus are less luminous, so starlight is probably an important contributor to them as well, even though they may be located further from the nucleus.

3.3 X-RAY IONIZATION AND ACCRETION LUMINOSITY

While x-rays must, at some level, contribute to the overall ionization of GC clouds, the observed x-ray luminosity (Watson *et al.* 1981) is far too small to account for the total ionization rate inferred for the GC.

We consider here the ionization by hard radiation and the luminosity resulting from accretion onto compact objects in the galactic center. If we assume that 1) GC stars formed according to a Salpeter IMF, $N(M)dM \propto M^{-2.35}$, 2) that the only stars which haven't evolved to form stellar remnants at their evolutionary endpoints are those with $M < 1\ M_\odot$, and 3) that all stars formed with masses between 30 and 60 $M_\odot$ are now black holes, then we can use the mass density distribution, $\rho(M_\odot\ pc^{-3}) = 3.5 \times 10^5\ r(pc)^{-1.8}$, (see reviews by Townes and Sellgren, this volume), along with reasonable assumptions about remnant masses, to derive the number density of black holes: $n_{bh} = 400\ pc^{-3}\ r(pc)^{-1.8}$. The assumptions about remnant masses negligibly affect this estimate. (We have also computed the number of white dwarfs and neutron stars in a similar way, but their contribution to the total accretion luminosity is only ~10% that of black holes, so we neglect them in this discussion.)

As a black hole accretes matter from a surrounding medium of density n_g by classical Bondi accretion, it produces an accretion luminosity of $L_{acc} = 9\ L_\odot\ \varepsilon M^2\ (n_g/10^4\ cm^{-3})$, where M is the black hole mass in solar masses and ε is the efficiency for conversion of gravitational to radiative energy. For this equation, the velocity dependence of the accretion rate has been averaged over a Gaussian distribution of stellar velocities having an RMS magnitude of 50 km s^{-1} (Sellgren, this volume). We assume, therefore, that this distribution of random velocities also reflects the distribution of relative velocities between stars and ambient gas clouds.

From the above, and adopting M = 10, we find that, within molecular clouds, the volumic accretion luminosity is $3.5 \times 10^5\ \varepsilon\ (n_g/10^4\ cm^{-3})\ r(pc)^{-1.8}\ L_\odot\ pc^{-3}$. For $\varepsilon = 0.1$ and $n_g = 10^4\ cm^{-3}$, this is about 20% of the stellar luminosity density. However, if significant mass segregation has taken place in the GC via statistical relaxation processes, or if the GC IMF is skewed toward massive stars relative to the Salpeter IMF, black holes with masses exceeding a few solar masses might be much more numerous than this calculation implies, and the luminosity would be correspondingly greater.

The calculated accretion luminosity, integrated over the estimated volume of molecular material in the GC, exceeds the observed x-ray flux, but it is not inconsistent with it if the spectrum of the emerging accretion luminosity is relatively soft ($kT < 1 - 2$ keV), in which case the radiation would almost all be absorbed within the cloud in which it was produced. Again, the x-ray ionization rate attributable to this process would not help account for the global ionization of the GC, but a 100 $M_\odot$ black hole (or a concentration of smaller ones) in a dense cloud might locally give the appearance of a compact HII region (consider, for example, some of the objects identified by Glass 1988).

4. Inhibition of Star Formation by Strong Magnetic Fields

It appears as if magnetic fields may be responsible for preventing molecular clouds in the galactic disk from collapsing to form stars on a free-fall time scale. According to Shu *et al.* (1987), low-mass stars can form in molecular cloud cores as the field escapes by ambipolar diffusion. High-mass stars, on the other hand, may form as a result of an event, such as a collision between clouds, which raises the ratio of cloud mass to magnetic flux, thus permitting gravitation to overwhelm magnetic pressure. This might happen as clouds merge along magnetic field lines which connect them, or as clouds having different field orientations merge, leading to annihilation of some of the flux (Shu 1987).

Do similar considerations apply to the galactic center? There are fundamental differences between the galactic disk and the galactic center: the geometry and strength of the magnetic field. The predominantly azimuthal magnetic field in the disk and its large non-uniformities ensure that most cloud collisions raise the mass to magnetic flux ratio relative to that in the individual colliding clouds. In the galactic center, on the other hand, the field appears to be predominantly poloidal and relatively uniform, at least in the inner 50 parsecs (Morris and Yusef-Zadeh 1989; Yusef-Zadeh, these proceedings). Therefore the field lines are perpendicular to the galactic plane and to the predominant motions of molecular clouds. Under these circumstances, the mass to magnetic flux ratio is not usually increased by cloud collisions; the field exerts a restoring force when clouds compress each other upon collision. Thus, we might imagine that high-mass star formation does not occur by the same mechanism in the galactic center as in the disk.

The strength of the field may also be a factor. With field strengths of at least a milligauss (Yusef-Zadeh and Morris 1987a,b, 1988), the field pressure is much larger than in the galactic disk, with the consequence that stable clouds in the galactic center region may have larger masses than those in the disk. Alfvén waves can be invoked to provide support for the cloud along the direction of the field, as described by Shu *et al.* (1987). Indeed, the observed Doppler half-widths of molecular lines in galactic center clouds (10 - 20 km s^{-1}; Güsten, these proceedings) are very similar to the Alfvén velocity of 15 km s^{-1} calculated for a molecular cloud having the typical density of 10^4 cm^{-3} and a milligauss field.

We conclude that magnetic support is especially effective in the galactic center region, and that any star formation which does occur requires a time comparable to the ambipolar diffusion time scale [10^8 yrs $(x/10^{-5})$ (R/10 pc), where x is the ionization fraction of the predominantly neutral cloud, and R is the characteristic scale length of the field]. The stars that thus form by the emergence of cloud cores may have relatively low masses, by analogy with the current view of star formation in the galactic disk.

5. Conclusions and Speculations

The arguments presented here indicate that one need not necessarily interpret the observed characteristics of the GC region in terms of current and ongoing formation of massive stars. Indeed, the magnetic field geometry, as well as its apparent strength, may be effective at inhibiting star formation under normal circumstances. The obvious question that remains, then, is how to account for the red supergiants observed near the galactic nucleus.

Here, we consider two alternative explanations, both of which involve episodic star formation. The first category invokes an explosive event which induces star formation in the dense clouds surrounding the nucleus, presumably by overcoming the magnetic pressure in the clouds. The expanding molecular ring and the galactic center lobe (see reviews in this volume by Sanders and Sofue) attest to the episodic occurence of explosive energy production in the GC. The production of the Sgr A East HII regions (G-0.02-0.07) by the compression associated with the expansion of Sgr A East (Goss *et al.,* this volume) may serve as a modest example of the process of induced star formation, while a starburst nucleus might be the extreme manifestation of it, wherein the original explosion is suitably amplified by the energy given off by newly-formed massive stars.

The second category of explanation is linked to the dynamo responsible for the magnetic field in the inner 50 pc. If, by analogy with other astrophysical dynamos, the poloidal field reverses polarity, then during the transition phase, the relatively massive GC clouds will either lose their magnetic support (if their internal fields can diffuse outward quickly enough), or they will be freed to rotate in response to tidal torques. In the latter case, the internal field orientations of the clouds would be randomized, and collisions between clouds could then result in field line annihilation. So, in either case, star formation becomes possible, and may even occur catastrophically (*i.e.*, as a starburst) if the first stars to form provoke a chain reaction in the "supersaturated" medium by virtue of their stellar winds and radiation pressure. Of course, the analogy with other astrophysical dynamos is tenuous at best (Rosner, this volume).

One might also speculate that explosions, star formation, and the dynamo are linked; the radial mass motions of clouds in the GC caused by explosions and/or starbursts may 1) be an essential element of a periodic dynamo, and/or 2) imply a future confluence of the currently expanding material into a relatively small volume near the nucleus, setting the stage for the next impulsive energy release from a starburst or from an accretion event such as, for example, that described by Sanders in this volume.

This work was supported by NSF grant AST87-18068 to UCLA.

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