INFRARED OBSERVATIONS OF THE GALACTIC NUCLEUS

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ABSTRACT

Infrared observations of the galactic nucleus and conclusions regarding the nature of the objects present there are reviewed. Observations of three sources of infrared radiation are discussed: near-infrared emission from cool stars, mid- and far-infrared emission from dust, and line emission from ionized gas. These observations provide information about the mass distribution, the stellar population, and the origin and ionization of the compact mid-infrared sources. The possibility of the existence of a massive central black hole is discussed.

1. INTRODUCTION

Much of what we know about the nucleus of our galaxy, especially its innermost parsec, has been discovered through infrared line and continuum observations. The large extinction to the center has made optical observations impossible. Radio observations have provided important information about the molecular and ionized gas near the center, but the spatial resolution of single dish measurements is $\sim$3 pc and the southern location of the galactic center has made interferometric observations difficult. The near infrared ($\lambda \lesssim 5\mu m$) continuum radiation is dominated by highly reddened emission from cool stars. Longer wavelength radiation comes predominantly from dust; the mid-infrared ($4\mu m \lesssim \lambda \lesssim 30\mu m$) from dust in and around the central H II region, Sgr A West, and the far-infrared ($\lambda \gtrsim 30\mu m$) from cooler dust, distributed throughout the nucleus. Hydrogen recombination and ionic fine-structure lines, found throughout the infrared spectrum, serve as probes of the motion, distribution, and ionization state of the ionized gas.

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2. OBSERVATIONS OF EMISSION FROM STARS

The nuclear star cluster was first detected by Becklin and Neugebauer (1968). They observed radiation at 1.65, 2.2, and 3.4μm, with a spatial extent similar to that of Sgr A. From the color of the observed radiation, assumed to be reddened starlight, they derived an extinction of A_v=27 mag, in reasonable agreement with that expected from dust in the galactic plane. Assuming the stellar population of the galactic nucleus is like that of the nucleus of M31, the 2.2μm brightness distribution indicates $L(r) \approx 2x10^6\ L_\odot\ (r/1\ pc)^{1.2}$ and $M(r) \approx 6x10^6\ M_\odot\ (r/1\ pc)^{1.2}$ for $0.5\ pc < r < 30\ pc$.

The angular distribution of near-infrared radiation has subsequently been observed by several authors. Becklin and Neugebauer (1975) mapped the central 1' (3 pc) with 2".5 resolution. About 1/3 of the emission from this region comes from a single bright source, IRS7, ∿1/3 from other discrete sources, and ∿1/3 from an extended background. IRS16, centered on the extended emission and essentially coincident with the compact radio source (Balick and Brown, 1974), may be the central peak of the stellar distribution. A map of the central 200 pc (Becklin and Neugebauer, 1979) shows the concentration of starlight toward the center, but the distribution is strongly influenced by variable extinction and bright sources. Lebofsky (1979) demonstrates that the 2.2μm intensity distribution is anticorrelated with H_2CO absorption. This observation implies that the observed 2.2μm distribution reflects the distribution of absorbing material more than that of the emitting stars. Maihara et al. (1978) have mapped the galactic bulge and disk to $|b|=10^\circ$. From a model of the inner part of the galaxy, they obtain the luminosities and extents of the bulge and disk as well as the distribution of dust. The bulge luminosity is $\sim 2x10^{10}\ L_\odot$, comparable to that of M31.

Spectra of the sources which are bright in the near-infrared confirm the stellar origin of at least some of this radiation. Neugebauer et al. (1976) observed CO absorption, like that found in cool stars, in IRS7, 11, and 12. IRS19 and the extended background have colors like those of the presumably stellar objects listed above (Neugebauer et al. 1978). IRS16, thought to be the central star cluster, has a similar spectrum although CO absorption has not been seen. IRS3 appears to be similar to the Becklin-Neugebauer object in Orion, a suspected protostar. High resolution observations of CO band heads in IRS7 give its velocity, $v_{LSR} = -163 \pm 90\ km\ s^{-1}$ (Treffers et al. 1976).

3. OBSERVATIONS OF EMISSION FROM DUST

Because intense radiation fields, such as those found in H II regions, are required to heat dust so that it emits mid-infrared radiation, the mid-infrared distribution often follows that of ionized gas. The angular distribution of mid-infrared continuum radiation has been mapped by Rieke and Low (1973), Becklin et al. (1975, 1978) and Rieke et al. (1978). Rieke et al. present a composite map of the central 5 pc with up to 0.075 pc resolution. A cluster of sources, each with a radius ∿0.1 pc, is seen in this region. As will be shown below, these sources are coincident with concentrations of ionized gas within Sgr A West.

Low resolution spectra of mid-infrared sources have been measured by Becklin et al. (1978) and Rieke et al. (1978). These sources peak near 10μm, as do compact H II regions, but 2.2μm emission is often detectable as well; some of the emission may be stellar or from unusually hot dust. The 2-13μm spectrum of the central region of the galactic center has been measured with ∿1% resolution by Willner et al. (1979), Soifer et al. (1976), and Woolf (1973). Except for the silicate peak near 10μm and several emission lines, which will be discussed below, the structure in this spectrum is due to interstellar absorption features in the intervening gas.

Capps and Knacke (1976) and Knacke and Capps (1977) have measured the polarization of the near- and mid-infrared radiation from various sources in the galactic center. The near-infrared polarization is approximately parallel to the galactic plane and probably results from extinction by aligned grains in the galactic disk. At 11.5μm, the polarization is rotated by ∿90° and varies from source to source. Presumably, this polarization results from extinction local to the infrared sources. The Davis-Greenstein grain alignment mechanism would require surprisingly large magnetic fields, $\sim 10^{-3}$ Gauss.

Far-infrared continuum emission comes largely from dust at temperatures of ∿100 K, found in cool gas. Most of the luminosity of the galactic nucleus is absorbed by dust and ultimately reradiated in the far-infrared. The angular distribution of this radiation reflects both the dust distribution and the stellar luminosity distribution. The far-infrared intensity has been mapped by Harvey et al. (1976), Gatley et al. (1977), Low et al. (1977) and Rieke et al. (1978). Two strong peaks are observed near the center; one centered on Sgr A West, the other on a weaker 10μm and radio continuum source, ∿45" southwest. The southwest source may be weak at shorter wavelengths due to obscuration. Multi-color observations indicate that the dust density is rather uniform; intensity variations result primarily from temperature variations. The temperature distribution is essentially that expected from heating by a distribution of luminous cool stars in the galactic bulge and ionizing stars concentrated toward the center. The column density of the dust, from which one could determine what fraction of the shorter wavelength extinction is local, has been debated.

4. OBSERVATIONS OF EMISSION FROM IONIZED GAS

Although mid-infrared continuum emission can be used as a tracer of the distribution of ionized gas and can provide an approximate measure of the ionizing flux, much more information can be obtained from ionic lines if they are observable. Hydrogen lines provide a direct measure of the ionizing flux and the ratios of various ionic lines measure both the spectral distribution of the ionizing radiation and the atomic abundances in the gas. Line shapes and Doppler shifts reflect the motions of the gas.

The first detection of an ionic emission line from Sgr A West was of Ne II (12.8μm) by Aitken et al. (1974, 1976). These observations confirm the thermal nature of the radio continuum emission and indicate that neon is predominantly singly ionized in the H II region unless it is substantially overabundant there. Ne II has subsequently been observed by Wollman et al. (1976, 1977), Willner (1978) and Lacy et al. (1979a, b). Wollman et al. resolved the line spectrally, finding a linewidth ∿200 km s^{-1} which indicates a virial mass $\sim 4 \times 10^6$ $M_\odot$ within a 1 pc radius. Lacy et al. resolved the Ne II line both spectrally and spatially. These observations show that most of the 10μm continuum sources are coincident with concentrations of ionized gas, each with a different velocity. These cloud velocities range over ±300 km s^{-1}. In addition to apparently random motions, there is an average rotation of the clouds about an axis nearly perpendicular to that of the Galaxy. The highest velocity clouds are found within ∿0.25 pc of the center, suggesting that the mass distribution is more centrally peaked than expected in an isothermal star cluster. The velocity distribution is best fitted by a central point-like mass (black hole ?) of $\sim 3 \times 10^6$ $M_\odot$ in addition to a distributed mass of $\sim 3 \times 10^6$ $M_\odot$ inside 1 pc.

Emission lines of several other ions have also been observed. Neugebauer et al. (1978) and Bally et al. (1979) measured the Brackett lines of hydrogen. The ratios of the intensities of these lines to the radio free-free intensity confirm the existence of ∿30 mag of visual extinction to the galactic center. Willner et al. (1979) have observed Ar II (7.0μm); Dain et al. (1978), O III (88μm); and Lacy et al. (1979a), Ar III (9.0μm). The abundance ratio $[Ar^{+2}]/[Ar^{+}]$ is ∿0.1, unusually low for a galactic H II region. The ionic abundances and abundance ratios require a source of ionizing radiation with an effective temperature, ≲35,000 K and a total Lyman continuum flux of $\sim 2 \times 10^{50}$ s^{-1}. One hundred O9V stars or somewhat fewer giants could produce such a spectrum.

5. CONCLUSIONS ABOUT OBJECTS PRESENT IN THE GALACTIC NUCLEUS

The nuclear mass distribution has been estimated in two ways. From the 2.2μm intensity distribution, Sanders and Lowinger (1972) calculate the mass within 1 pc of the center to be $\sim 4 \times 10^6$ $M_\odot$. The density appears to fall more slowly than the isothermal $\rho \sim r^{-2}$, but variable extinction makes this result uncertain. From the Ne II velocities, Lacy et al. (1979b) estimate the mass within 1 pc to be

6-12x10^6 $M_\odot$, ∿3x10^6 $M_\odot$ of which may be concentrated in a central black hole.

The stellar population of the galactic center is not well known. K and M giants are certainly present and dominate the near-infrared luminosity. IRS11, 12 and 19 have spectra and 2.2μm luminosities like those of M giants. IRS7, with L∿10^5 $L_\odot$ appears to be an M supergiant. If the ionizing radiation is provided by stars, a large number (∿100) of late O and early B stars must be present. For an equilibrium population of O and B stars to produce the ionizing radiation, the initial mass function must favor masses of ∿20 $M_\odot$ and have an upper mass limit of ∿30 $M_\odot$. Alternatively, an OB cluster of ∿10^4 $M_\odot$, formed ∿5x10^6 yr ago, would by now have evolved to produce the required ionizing spectrum. The hypothesis that massive stars are present near the galactic center is supported by the existence of IRS7, whose luminosity matches that of an evolved star of ∿15 $M_\odot$. The massive black hole suggested by the Ne II velocities could also be the source of the ionizing radiation. Accretion of ∿10^{-5} $M_\odot$ yr^{-1} onto a black hole of ∿2x10^6 $M_\odot$ would provide the required ultraviolet spectrum and luminosity. The near coincidence of this mass and that derived from the Ne II velocities is remarkable.

The coincidence of the Ne II clouds and the 10μm continuum sources demonstrates that these objects are concentrations of both dust and ionized gas. However, they differ in several ways from normal compact H II regions or planetary nebulae. First, the velocity dispersion of the gas within the clouds is sufficiently high (∿100 km s^{-1}) that only a few thousand years were required for the clouds to expand to their present sizes. Since a main sequence O star lives for >10^6 yrs, it could be surrounded by a compact H II region, formed from the cloud that collapsed to form the star, for only a very short part of its life. Second, the ionization state is unusually low for H II regions, and especially for planetary nebulae. Several explanations for this fact are suggested above. Third, the dust in these clouds is hotter and more luminous than that found in most H II regions.

Several models have been suggested for these objects. They may be hot spots in a relatively uniform distribution of gas and dust. Each source would be illuminated by an O giant or a cluster of main sequence O stars. Alternatively, the 10μm sources may be short-lived clumps, not associated with the source of ionizing radiation. The gas would be supplied by the ejection of planetary nebula shells or the disruption of stars in collisions, and the ionizing radiation could come from either a group of O stars or a central accreting black hole. The large turbulent velocities within and between the ionized clouds present a severe difficulty for the hot spot model. If the region is filled with gas, these turbulent motions should damp out within about one crossing time, ∿10^4 yr, unless they can be regenerated. No mechanism has been suggested to regenerate turbulence at the required rate. The transient clump model requires a considerable flow of mass,

$\sim 10^{-4}$ $M_{\odot}$ yr^{-1} either into a black hole or in and out of the central region. Large gas flows near the nucleus suggest that such a flow may not be unreasonable.

The presence of a massive central black hole has been suggested on several grounds. The motions of the ionized gas are best explained if a central mass $\sim 3\times10^{6}$ $M_{\odot}$ is present. However, the difference in probability between mass distributions with and without a central point-like mass is at the 1σ level. The presence of a massive black hole could also explain the unusually low ionization state of the region; less exotic explanations exist for this problem as well. The possibility of driving the molecular features which are expanding from the galactic center by radiation pressure from a black hole has been suggested in the past. Some source of large amounts of energy is needed to explain these features.

A determination of the mass distribution from stellar velocities, which are not influenced by non-gravitational forces, as are gas velocities, may be feasible. The measurement of ≳100 velocities would be required to obtain a statistically significant measurement of a deviation of the mass distribution from that of an isothermal star cluster. An exotic object, such as a massive black hole, seems almost to be required to explain the violent events which have occurred in some active galaxies. Young et al. (1978) and Sargent et al. (1978) suggest that a 5×10^{9} $M_{\odot}$ black hole is present at the center of M87. Perhaps we should not be surprised to find an object 10^{3} times smaller in our galaxy.

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REFERENCES

Aitken, D.K., Griffiths, J., Jones, B. and Penman, J.M., 1976, Mon. Not. R. Astron. Soc., 174, 41P.
Aitken, D.K., Jones, B. and Penman, J.M., 1974, Mon. Not. R. Astron. Soc., 169, 35P.
Balick, B. and Brown, R.L., 1974, Astrophys. J., 194, 265.
Bally, J., Joyce, R.R. and Scoville, N.Z., 1979, Astrophys. J., 229, 917.
Becklin, E.E., Mathews, K., Neugebauer, G. and Willner, S.P., 1978, Astrophys. J., 219, 121.
Becklin, E.E. and Neugebauer, G., 1968, Astrophys. J., 151, 145.
Becklin, E.E. and Neugebauer, G., 1975, Astrophys. J. Lett., 200, L71.
Becklin, E.E. and Neugebauer, G., 1979, Publ. Astron. Soc. Pac., 90, 657.
Capps, R.W. and Knacke, R.F., 1976, Astrophys. J., 210, 76.
Dain, F.W., Gull, G.E., Melnick, E. and Harwit, M., 1978, Astrophys. J. Lett., 221, L12.
Gatley, I., Becklin, E.E., Werner, M.W. and Wynn-Williams, C.G., 1977, Astrophys. J., 216, 277.

Harvey, P.M., Campbell, M.F. and Hoffman, W.F., 1976, Astrophys. J. Lett. 205, L69.

Knacke, R.F. and Capps, R.W., 1977, Astrophys. J., 216, 271.

Lacy, J.H., Baas, F., Townes, C.H. and Geballe, T.R., 1979a, Astrophys. J. Lett., 227, L17.

Lacy, J.H., Townes, C.H., and Hollenbach, D.J., 1979b, preprint.

Lebofsky, M.J., 1979, Astron. J., 84, 324.

Low, F.J., Kurtz, R.F., Poteet, W.M., and Nishimura, T., 1977, Astrophys. J. Lett., 214, L115.

Maihara, T., Oda, N., Sugiyama, T., and Okuda, H., 1978, Publ. Astron. Soc. Japan, 30, 1.

Neugebauer, G., Becklin, E.E., Beckwith, S., Matthews, K. and Wynn-Williams, C.G., 1976, Astrophys. J. Lett., 205, L139.

Neugebauer, G., Becklin, E.E., Matthews, K. and Wynn-Williams, C.G., 1978, Astrophys. J., 220, 149.

Rieke, G.H. and Low, F.J., 1973, Astrophys. J., 184, 415.

Rieke, G.H., Telesco, C.M. and Harper, D.A., 1978, Astrophys. J., 220, 556.

Sanders, R.H. and Lowinger, T., 1972, Astron. J., 77, 292.

Sargent, W.L.W., Young, P.J., Boksenberg, A., Shortridge, K., Lynds, C.R. and Hartwick, F.D.A., 1978, Astrophys. J., 221, 731.

Soifer, B.T., Russell, R.W. and Merrill, K.M., 1976, Astrophys. J. Lett., 207, L83.

Treffers, R.R., Fink, U., Larson, H.P. and Gautier, T.N., 1976, Astrophys. J. Lett., 209, L115.

Willner, S.P., 1978, Astrophys. J., 219, 870.

Willner, S.P., Russell, R.W., Puetter, R.C., Soifer, B.T., and Harvey, P.M., 1979, Astrophys. J. Lett., 229, L65.

Wollman, E.R., Geballe, T.R., Lacy, J.H., Townes, C.H., and Rank, D.M., 1976, Astrophys. J. Lett., 205, L5.

Wollman, E.R., Geballe, T.R., Lacy, J.H., Townes, C.H., and Rank, D.M., 1977, Astrophys. J. Lett., 218, L103.

Woolf, N.J., 1973, IAU Symposium No. 52, "Interstellar Dust and Related Topics", ed. J.M. Greenberg and H.C. van de Hulst (Dordrecht: Reidel) p. 485.

Young, P.J., Westphal, J.A., Kristian, J., Wilson, C.P. and Landauer, F.P., 1978, Astrophys. J., 221, 721.