DIAMETER AND PROPER MOTION OF SGR A*

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Abstract. The best hypothesis for the energy source of the compact, nonthermal radio source in the center of our galaxy, Sagittarius A* (Sgr A*), is accretion onto a massive black hole from winds emanating from nearby luminous stars. The hole mass, accretion rate, and ultimate fate of accreted matter are uncertain. In this report I give a summary of recent critical observations. The interpretation of these results supports this general hypothesis, and begins to place constraints on model parameters. If so, then Sgr A* is a miniature version of extragalactic AGNs in a quiescent state.

1. Introduction

Infrared speckle imaging results of the central stellar distribution, reported by Eckart *et al.* (1993) and updated by R. Genzel during this IAU meeting, lead to the strong conclusion that Sgr A* is *at* the dynamical center of the Galaxy. However, in spite of its location and the summary remarks in the abstract, Sgr A* remains an enigmatic object: we have no firm information on the *intrinsic* brightness distribution of Sgr A*; there is no widely accepted estimate of the mass of the underlying body; and there is no convincing model for the emission mechanism(s). In this short account I will summarize recent measurements of its angular diameter at millimeter wavelengths and the proper motion of Sgr A*. A longer account may be found in Backer (1994), and a review of our understanding of the central 100 parsecs may be found in review article by Genzel, Hollenbach and Townes (1994).

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2. Models

Models for the radio emission from Sgr A* have varied widely. Reynolds & McKee (1980) considered mass outflow from a stellar mass energy source. Rees (1987) discusses a model involving accretion onto a massive black hole from the disruption of stars in the central stellar cluster. Ozernoy (1989; 1993; 1994) concludes that if the radiation arises in matter accreting onto a massive black hole from nearby stars, then the hole mass is less than 10^3 $M_\odot$. In his model a spherical halo of electrons, which are heated to relativistic speeds as they fall into the hole's deep potential well, emit optically thin synchrotron radiation. Melia (1992; 1994) and Ruffert & Melia (1994) calculate that a 10^6 $M_\odot$ black hole will accrete $\dot{M}$ of 10^{-4} $M_\odot$ y^{-1} with low specific angular momentum from the wind emanating from the nearest object in the IRS 16 complex. He computes the flux spectrum from electrons that are heated to near relativistic temperatures as they fall spherically into the black hole potential. The embedded magnetic field is an additional energy source as it is assumed to stay in equipartition during infall. Additionally he identifies the source observed by Sigma/GRANAT at the position of Sgr A* (Sunyaev *et al.* 1991) as the thermal bremsstrahlung counterpart of the electrons which create the radio spectrum via magnetic bremsstrahlung. Goldwurm *et al.* (1994) conclude from the extremely low level of Xray flux above 30 keV that the mass is much less then 10^6 $M_\odot$ in spite of Melia's calculations. Falcke *et al.* (1993) provide a third view. They assume a much lower accretion rate of 2×10^{-8} $M_\odot$ y^{-1} onto a 10^6 $M_\odot$ hole, and form the radio emission spectrum in a relativistic jet that is expelled from a disk around the hole and whose length is below observability.

3. Intrinsic Brightness Distribution and Interstellar Scattering

High angular resolution VLBI techniques have been used to probe the brightness distribution of radiation from Sgr A* (Lo *et al.* 1985; Jauncey *et al.* 1989; Alberdi *et al.* 1992; Lo *et al.* 1993). These long wavelength results indicate an apparent East-West diameter of (1.40 ± 0.05) $(\frac{\lambda}{\mathrm{cm}})^{2.0}$ mas. The visibility data at λ 3.6cm fit a profile that is very closely gaussian along both major and minor axes of the apparent source brightness distribution. The ellipticity is 2:1. Observations with the inner VLBA antennas at λ 7mm are very consistent with the extrapolation of the anisotropic image sizes (Backer *et al.* 1993; Krichbaum *et al.* 1993). VLBI measurements on the HSTK-KTPK-OVRO baselines in 1994 April at λ 3mm place limits on the diameter of the source and strongly suggest that scattering is still dominant along the major axis at these short wavelengths (Fig. 1; Rogers *et al.* 1994). Krichbaum *et al.* (1994) have resolved Sgr A* at λ 3mm on the Pico Velata-Effelsberg baseline (PA 245°), and suggest that intrinsic struc-

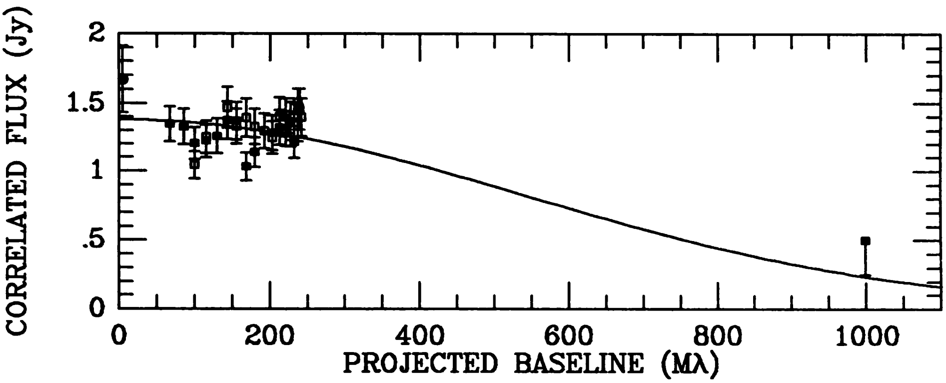

Figure 1. Visibility of Sgr A* at λ 3mm wavelength as a function of projected baseline in wavelengths using the BIMA interferometer (short baseline value) and a VLBI experiment involving OVRO, NRAO Kitt Peak (KTPK) and Haystack telescopes. The transcontinental baselines at about $10^9\lambda$ resulted only in an upper limit. The baselines are predominantly East-West. A model visibility curve for a circular gaussian source with full width at half maximum of 0.16 milliarcseconds, which is consistent with the lack of resolution on the OVRO-KTPK baseline, is shown. This diameter is consistent with extrapolation of interstellar scattering effects from longer wavelength values.

ture may be present. VLA observations at λ 20 cm are also consistent with the wavelength dependence of the size (Backer 1988) and the asymmetry of the intensity distribution (Yusef-Zadeh *et al.* 1994).

The simplest explanation for the wavelength dependent size is interstellar diffractive scattering of an intrinsic source brightness distribution that is always much smaller than the observed size. The large amplitude, anisotropic scattering probably arises in a region near the galactic center. The 2:1 asymmetry of the blurred image may be interpreted as evidence of anisotropy in the turbulence due to strong magnetic fields (Higdon *et al.* 1984, 1986; Goldreich & Sridhar 1994). The interstellar scattering interpretation has received strong confirmation from observations of the strong scattering of OH masers near Sgr A* (van Langevelde *et al.* 1992). Frail *et al.* (1994) have recently shown that the scattering of these OH masers is also anisotropic with random position angles.

In conclusion we have *no* solid evidence for a finite size to the intrinsic brightness distribution at cm and mm wavelengths. The λ 3mm observations place an *upper* limit on the source diameter of 1 AU and a corresponding *lower* limit to the brightness temperature of 10^{10} K. VLBI observations at even shorter wavelengths could peer through the interstellar scattering at the intrinsic brightness distribution, although the existence of a submm component (Zylka, Mezger & Lesch 1992; Carlstrom, Lay & Hills 1993) will be confusing.

4. Proper Motion

NRAO's VLA has been used from 1981 to 1988 to measure the apparent proper motion of Sgr A* relative to three compact radio sources with separations from Sgr A* of less than 1° (Backer & Sramek 1987). The estimated proper motion and estimated 2σ errors is:

$$(\mu_l,\ \mu_b) \ = \ (-6.55 \pm 0.34,\ -0.48 \pm 0.23)\ \mathrm{mas\ y^{-1}}.$$

These values can be compared to those that one would expect for an object at rest at the galactic center – a secular parallax – $(-6.21,\ -0.19)$ mas y^{-1} for a choice of the solar motion of 220 km s^{-1} and a choice of the solar distance $R_\odot$ of 8.0 kpc (Reid 1993). The measured value agrees closely with the secular parallax. An upper limit on the transverse peculiar motion of Sgr A* is then, $(-13 \pm 13, -11 \pm 9)$ km s^{-1}.

If Sgr A* is 'just' a star buzzing around in the equipotential well of the galactic center, then it is most likely in equipartition with the detected IR stars. Sellgren *et al.* (1990) have shown that low (solar) mass stars in the central parsec have a velocity dispersion of about 125 km s^{-1}. On the other hand, if the presumed higher mass He stars in the central 0.3 pc have a similar, or even higher, velocity dispersion (Eckart *et al.* 1993), then the equipartition energy for Sgr A* could be at least an order of magnitude higher. The lower limit to the mass of Sgr A* is then at least 100 $\mathrm{M}_\odot$, and could be larger by an order of magnitude.

5. Conclusions

Sgr A* is a unique radio source in the very center of the galaxy. It spectrum suggests an inhomogeneous, optically thick synchrotron source. VLBA observations show that the intrinsic size of the λ 3mm source is not more than one AU. The mass of the central body most likely exceeds 100 $\mathrm{M}_\odot$ based on a proper motion measurement and the observed stellar velocity dispersion. A black hole that is large in stellar mass units is indicated, and starved accretion onto this object is the leading candidate for energy source that generates the spectrum of Sgr A*. There is wide disagreement on further details. Variations of the accretion rate and instabilities in the inflow can easily be associated with the observed variability.

There is considerable room for improvement of our knowledge of Sgr A* from cm/mm observations: searches for linear polarization with extremely large Faraday rotation, a more accurate estimate of its peculiar velocity with VLA and VLBA measurements, analysis of temporal variability, investigation of structure on the scale of our solar system with higher dynamic range VLBI observations, and investigation of structure on the AU scale with shorter wavelength VLBI observations are all possible with new instrumentation and new techniques within our grasp.

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