DETECTION OF SAGITTARIUS A* AT 330 MHz WITH THE VERY LARGE ARRAY

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ABSTRACT

We report the detection of Sgr A*, the radio source associated with our Galaxy’s central massive black hole, at 330 MHz with the Very Large Array. Implications for the spectrum and emission processes of Sgr A* are discussed and several hypothetical geometries of the central region are considered.

Subject headings: Galaxy: center — Galaxy: nucleus

1. INTRODUCTION

The central radio-bright region of our Galaxy, known as the Sagittarius Complex, is composed of three major components: the supernova remnant (SNR) Sgr A East, the Sgr A West H II region, and Sgr A*, recently established as our Galaxy’s central massive black hole (e.g., Ghez et al. 2000; Eckart et al. 2002).

Models attempting to explain the emission from Sgr A* fall into three broad classes. Emission is modeled as arising from thermal sources, such as a low-temperature accretion disk, from nonthermal sources such as a jet (e.g., Melia & Falcke 2001 and references therein), or from a mixture of the two. Such models are constrained primarily by the observed spectrum of Sgr A*, but large gaps in frequency coverage exist. For this reason, filling such gaps, as with the recent near-IR detections (Ghez et al. 2000; Genzel et al. 2003), and extending the range of frequencies over which the source is observed is important in order to place additional observational constraints on these models.

Davies, Walsh, & Booth (1976) attempted to observe Sgr A* at 410 MHz but reported no detection above a level of 50 mJy. The first Very Large Array4 (VLA) images of the Galactic center (GC) at 330 MHz (Pedlar et al. 1989; Anantharamaiah et al. 1991) represented a major improvement in sensitivity and resolution over previous meter wavelength images. Pedlar et al. did not detect Sgr A* down to a 5σ level of 100 mJy. Although Anantharamaiah et al. had higher sensitivity (rms ~5 mJy beam−1), they also reported a nondetection. The absence of any detections below 1000 MHz was interpreted as thermal absorption obscuring Sgr A*, indicating that the low-frequency properties of Sgr A* are dominated by extrinsic absorption, not intrinsic emission.

New low-frequency detections of Sgr A*, including the first detection of the source below 1 GHz (610 MHz; Roy et al. 2003), and this 330 MHz detection suggest that the low-frequency properties of Sgr A* are constrained primarily by the observed spectrum of Sgr A*, but large gaps in frequency coverage exist. For this reason, filling such gaps, as with the recent near-IR detections (Ghez et al. 2000; Genzel et al. 2003), and extending the range of frequencies over which the source is observed is important in order to place additional observational constraints on these models.

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TABLE 1

| Epoch   | Configuration | v (MHz) | Δv (MHz) | Integration (hr) |
|---------|---------------|---------|----------|-----------------|
| 1996 Oct | A             | 332.5   | 6        | 5.6             |
| 1998 Mar | A             | 327.5   | 3        | 5.4             |

3.2. The Detection of Sgr A*

Figure 2 shows slices through the assumed major and minor axes of Sgr A*. Gaussian fits with baseline subtraction to these slices results in a measured source size of (17′6 ± 4′′) × (15′9 ± 5′′), a peak intensity of 80 ± 15 mJy beam−1, and a total flux density of 330 ± 120 mJy. The source deconvolved with the 6′8 × 10′9 beam gives a source size of (16′′ ± 4′′) × (11′′ ± 5′′). If the source is fit in the image instead of fitting slices, the position angle is then a free parameter instead of assumed to be 80°. A two-dimensional Gaussian fit of the region yields a position angle of 35° ± 35°. However, this fit is contaminated by flux density to the south of the source as shown in the slice on the right in Figure 2.

The location and flux density of the source agree with the extrapolations of § 3.1, and the size of the source agrees to within ~1.2 σ along the assumed minor axis and ~1.1 σ along the assumed major axis. However, an alternate interpretation of this emission is that it originates from the Sgr A East SNR.

The absorption in Figure 1 is caused by the Sgr A West H II region, first detected in absorption by Pedlar et al. (1989). The Sgr A West H II region is composed of a dense region known as the “minispiral” (Lo & Claussen 1983; Ekers et al. 1983), known to be orbiting Sgr A* (Roberts and Goss 1993), and a more diffuse ionized region ≈80′ × 60′ in size, known as Sgr A West (extended; Mezger & Wink 1986; Pedlar et al. 1989). Both components of Sgr A West are detected in thermal (free-free) absorp-
tion against the Sgr A East SNR with 330 MHz optical depths \( (\tau_{330}) \) greater than 1 across a large portion of the \( \text{H} \, \text{ii} \) region (Pedlar et al. 1989). The position of Sgr A* is offset from the minispiral (Zhao & Goss 1998); therefore, in order for Sgr A East to be absorbed at the position of Sgr A*, most of the absorption must arise from Sgr A West (extended). Estimates of the optical depth along lines of sight near Sgr A* based on higher frequency measurements \( (\nu = 5 \, \text{GHz}; \text{Yusef-Zadeh & Morris 1987}) \) suggest that 330 MHz optical depths near Sgr A* are \( \tau_{330} \sim 10 \). Moreover, any gap through the Sgr A West \( \text{H} \, \text{ii} \) region would have to occur with the size, shape, and location necessary to allow Sgr A East to be detected with the expected size, shape, and flux density of Sgr A*. Given the agreement in observed and predicted source properties, the likelihood that Sgr A East is detected can be discounted. We conclude that we have detected Sgr A* at 330 MHz.

4. IMPLICATIONS

4.1. Previous Nondetections

Previous nondetections at similar frequencies can be attributed to the limited sensitivities of the observations. Davies et al. (1976) observed using the Mk I–Defford interferometer. This two-element interferometer has a north-south resolution of \( \theta \approx 2.7' \) at 408 MHz. The correlated flux density that would have been measured by this interferometer is \( S_{\text{corr}} = S_n e^{-\theta v^2} \), where \( \theta \) is the scattering diameter and \( S_n \) is the intrinsic flux density (Roy et al. 2003). The expected scattering diameter of Sgr A* is 4". Their upper limit, \( S_{\text{corr}} \sim 50 \, \text{mJy} \), implies that they would not have detected any source weaker than 0.9 Jy, a value that is well above the flux density that we have observed at 330 MHz.

Pedlar et al. (1989) observed the GC with the VLA. At the time of their observations, only a few (\( \sim 10 \)) of the 27 VLA antennas were outfitted for 330 MHz observations. In addition to a higher thermal noise level \( (\text{rms sensitivity} \approx 16 \, \text{mJy beam}^{-1}) \), the number of baselines was substantially lower, resulting in less complete \( u-v \) coverage. Sgr A* would have been only a 3 \( \sigma \) source in a crowded and confusing field.

Anantharamaiah, Pedlar, & Goss (1999) reanalyzed data from Anantharamaiah et al. (1991) in which the GC was observed at 330 MHz with all antennas of the VLA. In their Figure 2, there is a hint of a detection of Sgr A* at a level of \( \sim 40 \, \text{mJy beam}^{-1} \), which is consistent with this detection. The authors do not comment on this possible detection.

4.2. The Spectrum of Sgr A*

Figure 3 shows the observed spectrum for Sgr A*, including our flux density measurement. This spectrum is not constructed from simultaneous measurements, and because Sgr A* is variable, simultaneous measurements may show differences.

There are at least two models of the low-frequency spectrum of Sgr A* that are suggested by our detection. Either the \( S_0 \sim \nu^{-0.3} \) spectrum observed across the centimeter radio band continues toward low frequencies and the source is unobscured by intervening thermal gas, or the spectrum of Sgr A* rises below \( \sim 1 \, \text{GHz} \) and is obscured by significant optical depth.

Assuming a \( S_\nu \sim \nu^{-0.3} \) spectrum, a 330 MHz optical depth of \( \tau_{330} < 0.1 \) is required to explain the measured Sgr A* flux density. Even a flat spectrum below 1.4 GHz permits an optical depth of only \( \tau_{330} \sim 0.4 \). Therefore, the free-free optical depth along this line of sight is much less than the \( \tau_{330} \sim 3-5 \) previously assumed to explain low-frequency nondetections (Pedlar et al. 1989).

A conclusion of § 3.2 is that lines of sight to Sgr A East that pass near Sgr A* have large 330 MHz optical depths. If the line of sight to Sgr A* were similarly obscured, its intrinsic flux density would have to be increasing at low frequencies in order to agree with the observed flux density. The optical depth has a frequency dependence of \( \nu^{-2.1} \). In order to agree with the observed flux density, the intrinsic flux density would have to rise exponentially \( \left( S_0 \propto e^{t_0} \right) \) below \( \sim 1 \, \text{GHz} \).

Low 330 MHz optical depths near Sgr A* are also indicated by the 22 GHz, 0.1 resolution image of the Sgr A* region by Zhao & Goss (1998), which shows emission measures due to ionized gas within 0.2 of Sgr A* are nearly 2 orders of magnitude lower than in the nearby minispiral. Furthermore, an exponential rise in intrinsic flux density to almost exactly cancel the large (factor of \( \sim 10 \) between 1000 and 330 MHz) increase in free-free optical depth at 330 MHz would be quite improbable.

We conclude that it is likely that there is little or no free-free absorption along the line of sight to Sgr A*, and that the observed flux density is intrinsic to the source. Our results imply a large optical depth toward the Sgr A East SNR, but a small optical depth toward Sgr A*. This could be explained by a localized clearing of the ambient gas accomplished either through the direct influence of the black hole, or through the stellar winds of the central cluster. It is also possible that the ionized medium in the GC region is clumped, with the line of sight to Sgr A* passing through a gap. Our data cannot differentiate between these possibilities.

4.3. Emission Mechanisms

Previous modeling of the spectrum of Sgr A* did not have to confront its flux density at low frequencies, because Sgr A* was thought to be unobservable below 1 GHz (e.g., Mahadevan 1998). Furthermore, the 410 MHz nondetection of Davies et
al. (1976) is often incorrectly treated as an upper limit. Our 330 MHz result and the 610 MHz detection by Roy et al. (2003) require these models to be reevaluated. Because we cannot exclude the possibility of free-free optical depth toward Sgr A*, our reported 330 MHz flux density should be considered a lower limit.

Advection-dominated accretion flow (ADAF) models (e.g., Yuan, Markoff, & Falcke 2002) predict flux densities nearly 2 orders of magnitude lower than the 330 MHz measurement. The relativistic jet+ADAF model of Yuan et al. (2002) does not explicitly make predictions below 1.4 GHz but would appear to closely match the measured 330 MHz flux density. It should be noted that in the jet models, low-frequency emission arises from farther out along the jet, probing regions farther from the event horizon.

5. CONCLUSIONS

We have presented a new high-resolution, high-sensitivity image of the Sgr A region at 330 MHz, constructed from observations at multiple epochs with the Very Large Array. We report a detection of Sgr A*, with a flux density of 330 ± 120 mJy. Previous nondetections of Sgr A* at comparable frequencies are attributable to the poor sensitivity and/or $u$-$v$ coverage of the interferometers used.

We argue that only small amounts of free-free absorption ($\tau_{330} \sim 0.1$) exist along the line of sight to Sgr A* and therefore that Sgr A* is observed through a region of low density in the Sgr A West H II region. It is possible that the intrinsic spectrum of Sgr A* rises below ~1 GHz. However, the intrinsic rise in flux density would have to be balanced by free-free absorption to result in the observed value. Therefore, this flux density measurement is a lower limit to the intrinsic flux density of this source as the optical depth along the line of sight remains unknown (e.g., Anantharamaiah et al. 1999).

This detection at 330 MHz, combined with the recent detection at 610 MHz (Roy et al. 2003), expands the frequency range over which Sgr A* has been detected and allows for low-frequency observational constraints on Sgr A* emission mechanisms. Future observations at and below 240 MHz with the Giant Metrewave Radio Telescope and the Low Frequency Array (Kassim et al. 2000) may expand the frequency range at which Sgr A* is detectable to even lower frequencies.

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