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A high resolution H I absorption spectrum of Sgr A*

H. S. Liszt[1], W. B. Burton[2], and J. M. van der Hulst[3]

[1] National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901, USA
[2] Sterrewacht Leiden, Postbus 9513, NL-2300 RA Leiden, The Netherlands
[3] Netherlands Foundation for Radio Astronomy, Radiosterrewacht Westerbork, Schattenberg 4, NL-9433 TA Zwiggelte, The Netherlands

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Summary. We have used the VLA to obtain an H I absorption spectrum of the compact source Sgr A* in the galactic nucleus at an angular resolution of 1″.5. Absorption at 40–60 km s^{-1} is present at an optical depth $\simeq$0.25, as in our earlier, lower-resolution H I data (Liszt et al., 1983). The absence of such gas in the recent H_2CO absorption synthesis of Whiteoak et al. (1983) at 3″.5 resolution must therefore be ascribed to peculiarities in the absorbing material and perhaps to the $\simeq$130 times larger solid angle of Sgr A* at λ21 cm. It cannot be due only to a background source geometry in which Sgr A* is physically removed from the thermally-emitting material which appears to surround it.

Key words: galactic center – H I regions – interstellar clouds – interstellar absorption

1. Introduction

Recently, we published a discussion of the H I absorption patterns observed over Sgr A with 12″ spatial resolution (Liszt et al. 1983). One of the principal results of that work was the detection of absorption at 40–60 km s^{-1} around and toward the compact non-thermal radio source within Sgr A West, which we call Sgr A*. Previous lower-resolution surveys of H I (Schwarz et al. 1982) and H_2CO (Whiteoak et al. 1974) did not reveal this source. By contrast, the recent H_2CO observations of Whiteoak et al. (1983) at *higher* spatial resolution, 3″.5, did find 40–50 km s^{-1} absorption toward portions of the thermal emission around Sgr A* (Ekers et al. 1983), but none exactly toward it.

The striking absence of the compact source in the line channel map of Whiteoak et al. at these velocities forces consideration of the disquieting possibility that the compact source is not co-located with the thermal gas appearing around it (i.e. Sgr A West). If this possibility is taken seriously, differences between the higher-resolution H I and H_2CO observations might be ascribed to the larger beam of the former and to the preponderance of non-thermal emission at λ21 cm. The H I optical depth might have arisen against extraneous portions of the continuum in the vicinity of Sgr A*, and not toward the compact source itself. There are, of course, other explanations of the H_2CO results. If the molecular and atomic gases are not well-mixed, the more fragile molecular material might be disrupted or its kinematics might be disturbed very near the galactic nucleus (Whiteoak et al. 1983). Alternatively, the H_2CO level populations could be drastically altered or the molecular gas might be clumped in such a way that Sgr A* is simply not occulted. Although the apparent optical depth in H_2CO is large toward the eastern portions of the Sgr A continuum (and the covering factor must therefore be of order unity), there very clearly exist large changes in the gas across the innermost nuclear regions.

Even though the 40–60 km s^{-1} H I absorption did appear in an independent observation having an effective beam size $\simeq$4″ (see Fig. 1 of Liszt et al., 1983), it seemed desirable to reobserve the atomic gas with the highest available usefully angular resolution and so perhaps decide among the various possible explanations. The compact source actually appears quite large at the H I wavelength, 0″.6 (Lo et al., 1981): in general, the source size varies as $\theta(\lambda)\propto\lambda^2$, perhaps due to interstellar scattering (Davies et al., 1976). Given this situation, we used the VLA rather than the VLBI network.

Send offprint requests to: W. B. Burton

2. Observations

The new observations presented here were taken on 1983 November 19 using 13 antennas of the VLA A-configuration (which has a maximum fringe separation of 1″), and 128 spectral channels separated by 5.2 km s^{-1} as in our earlier work. The antennas were spaced over the array in the hope of mapping at high resolution but, as shown below, only the compact source and a very small fraction of the extended flux could be detected.

The spectrum shown in Fig. 1 is the vector average of all the newly available data. In such an average, the phase rotation undergone by regions away from the phase center of the observations (Sgr A*) serves to cancel their contribution, leaving significant response over only a small angular area. In this experiment, even our shortest baselines contributed very little to the vector average. Several line profiles produced by eliminating these shorter baselines to varying degrees did not differ except insofar as the noise was increased with fewer baseline pairs contributing. The spectrum in Fig. 1 was phase and bandpass calibrated by observing 1748–253, 3C286, and 3C84, and a small linear baseline was subtracted, but no deconvolution (such as CLEAN) was employed.

By contrast, the continuum map in Fig. 1 was more heavily processed, i.e., self-calibrated and CLEAN-deconvolved. This map is hardly definitive and is shown only to demonstrate explicitly that a high spatial resolution (HPBW 1″.5) was obtained. No effort was expended to improve on the absolute flux density scale resulting from the on-line procedures (and observation of 3C286).

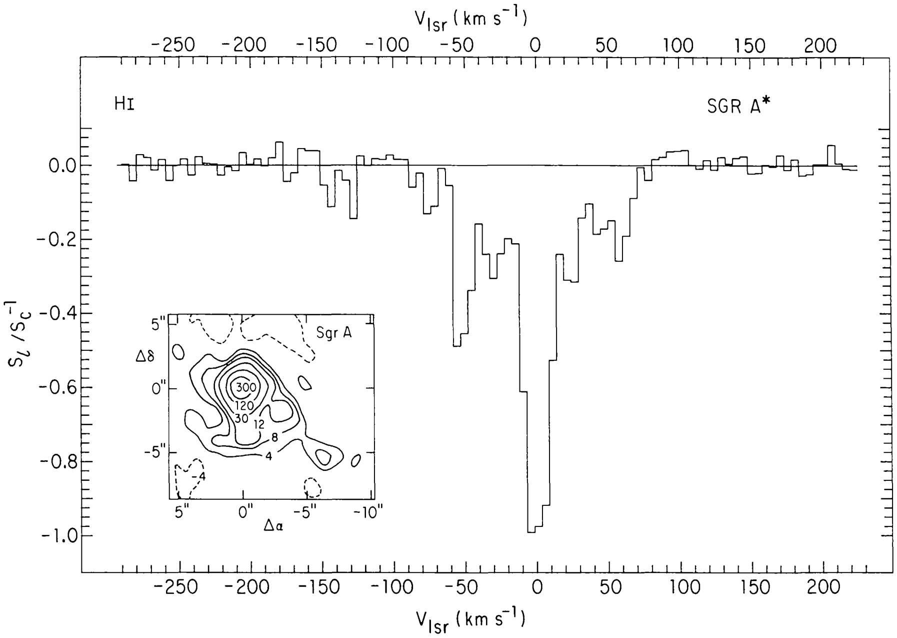

Fig. 1. Vector-average H I absorption spectrum of the compact source Sgr A* measured at the VLA with ≦1″.5 spatial resolution and 5.2 km s^{-1} velocity resolution. The ordinate is line/continuum $-1(=e^{-\tau}-1)$ and the noise level in that quantity is $\sigma_{1/c}=0.023$. *Insert:* Continuum distribution arising from this work, with FWHM 1″.5. Contours are labelled in mJy/beam; peak flux is 630 mJy/beam. Coordinates for the insert are relative to Sgr A* at 17^{h}42^{m}29^s.335, −28°59′18″.6

The peak flux density in the map, 630 mJy/beam, may be some 20% low (van Gorkom, private communication) but this is irrelevant to determining the line/continuum ratio. The H I spectrum corresponds most closely to that one which would have been obtained by mapping all the data and extracting information at the central cell of the continuum distribution. The one-sigma error in the line/continuum ratio, obtained after some 3.5 hours on Sgr A*, is $\sigma_{1/c}=0.023$.

3. Discussion

a) Why H I *and not H_2CO?*

Within the noise, the new H I spectrum is identical to that displayed in our earlier work: the apparent optical depth of the 40–60 km s^{-1} gas is unchanged ($\tau_{\rm HI}\simeq 0.25$) and all features visible in the earlier data are present in the newer work. The most noticeable difference occurs in the weak feature at −135 km s^{-1} which now appears to have a double structure. Because the spatial resolution is higher than that of Whiteoak et al. (1983), and because the 40–60 km s^{-1} H I absorption can only arise toward Sgr A*, differences between the H_2CO and H I can only be ascribed to chemistry, excitation, or clumping in the molecular gas. The compact source indisputably lies behind material at 40–60 km s^{-1} which just does not appear in the molecular absorption. Actually, there are several features, at both positive and negative velocity, which are detected only in the H I.

Except for clumping, the various possible explanations of the H_2CO behaviour demand that the absorbing gas be located very close to Sgr A*; any hole in the H_2CO distribution responsible for the 40–50 km s^{-1} absorption is no larger than the 3″.5 resolution of the H_2CO data. The presence of dense neutral gas very close to the nucleus seems at odds with observations of the 10–100 μm infrared continuum (Becklin et al., 1982), which show that the dust density strongly decreases, and the gas temperature greatly increases, within 1 pc of the galactic center. These results and detailed correspondence between the structure of the 10 μm and 6 cm continua (Brown et al., 1981) imply that gas interior to 1 pc is ionized.

Clumping is attractive only to the extent that it is permitted by the apparent optical depth of the 40–50 km s^{-1} H_2CO. The regions projected around Sgr A* are absorbed at a fairly uniform level $\tau_{\rm app}\simeq 0.10$, which implies that the covering fraction $f_\Omega \geqq 0.1$ as well. The true optical depth inside any absorbing clumps, $\tau_{\rm true}$, is related to f_Ω and $\tau_{\rm app}$ by

$$f_\Omega=\frac{(1-e^{-\tau_{\rm app}})}{(1-e^{-\tau_{\rm true}})} \qquad (1)$$

and $\tau_{\rm true}\leqq 1$ for $f_\Omega \leqq 0.16$. There is certainly sufficient leeway in the observations to permit a low covering factor at reasonable clump opacities. Whether such an interpretation is correct, however, remains to be confirmed using mm interferometry.

The atomic and molecular gases need not be entirely separate in order that the clumping interpretation succeed. Because of the scattering, the compact source appears to have a solid angle larger by a factor $(4830/1420)^4=134$ [$\simeq(0''.6/0''.5)^2$] at the H I line frequency (Lo et al., 1981) and this is probably true as well at the location of the absorbing neutral material. Thus there is a much larger chance that at least *some* of the gas around Sgr A* will be occulted at λ21 cm. The observations could be accommodated if, for instance, the absorbing material had a gap corresponding to an angular diameter of 0″.15. Such a structure would be an order of magnitude larger than Sgr A* at λ6 cm and an order of magnitude smaller at the H I line.

b) Is Sgr A in the galactic nucleus?*

Although the H_2CO absorption measurements can (and most plausibly should) be understood without recourse to removing Sgr A* from the structure seen around it, it cannot be denied that the compact source does occupy a slightly odd position relative to that structure in several regards. It lies some 2″ away from the intensity centroid of the thermal emission (Ekers et al., 1983) or

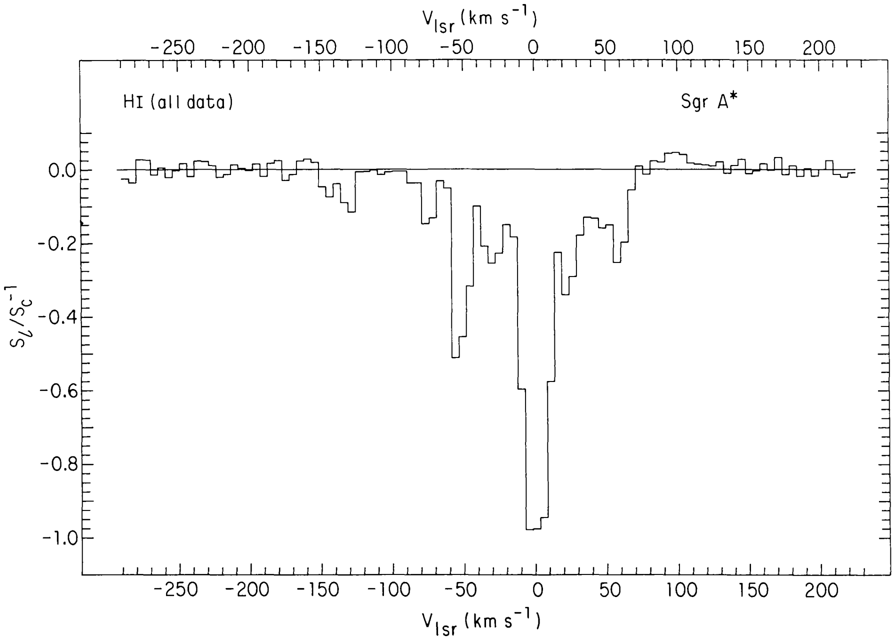

Fig. 2. H I absorption spectrum toward Sgr A* obtained by adding the data of Fig. 1 to the vector-average spectrum of Liszt et al. (1983); the noise level is $\sigma_{1/c}=0.017$

from the apparent kinematic center of that gas (Lacy et al., 1980). Even more perplexing is the apparent separation between Sgr A* and IRS16, the latter taken to be the central star cluster in the nucleus (Storey and Allen, 1983). Again, it is tempting to hypothesize that Sgr A* is an interloper in this region, perhaps even an extragalactic background source.

Because the two vector-average spectra we have produced appear so similar, we have added them to produce a lower-noise profile in Fig. 2. A salient property of this line is the presence of only one of the two "expanding" features which appear over substantial portions of the galactic center region (Liszt and Burton, 1978), crossing zero-longitude at -135, $+165$ km s^{-1}. Both of these are ubiquitous in emission, but only the first has ever been seen in absorption against continuum sources in the galactic center – the $+165$ km s^{-1} gas appears in H_2CO absorption against the black-body background radiation (Bieging et al., 1980) – and the general presumption is that they are fairly symmetrically disposed on opposite sides of the galactic nucleus. Although not impossible, it is unlikely that a distant background object would avoid occultation by H I in the $+165$ km s^{-1} feature. The H I absorption measurements seem to rule out any interpretation placing Sgr A* very far from the galactic center.

4. The sources of 40–60 km s^{-1} absorption toward Sgr A

All the various components of Sgr A have now been shown to be occulted by gas in the range 40–60 km s^{-1}. This statement refers to Sgr A (East), and so to the entire non-thermal shell whose western rim is projected against Sgr A* (Ekers et al., 1983), to the thermal emission spiral around Sgr A*, and now, to Sgr A* itself. Perhaps we may now forget the decade-old controversy regarding which parts of Sgr A are in front, and which are behind, this positive-velocity gas (see Whiteoak et al., 1974). Apparently, they are all behind it.

The matter is complicated, however, because it appears that there is actually more than one source of absorption at these velocities. As discussed in the second section of the companion paper (Liszt et al., 1984), only that absorption toward the eastern, non-thermal portions of Sgr A arises from the extended 50 km s^{-1} molecular cloud whose front-back positioning with respect to Sgr A has heretofore been controversial. The H I absorption toward and immediately around Sgr A* arises from a ring of material which can be traced in spectra of H I and CO some 3 pc from the nucleus: its kinematics are definitely not those of the 50 km s^{-1} molecular cloud. This ring structure in the neutral gas can be followed to smaller distances at infrared wavelengths (Becklin et al., 1982) and is related to the appearance of the spiral morphology around Sgr A* (Brown and Liszt, 1984). For further discussion, we refer the reader to Brown and Liszt (1984) and to Liszt et al. (1984).

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