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Letter to the Editor

Interferometric observations of FeO towards Sagittarius B2

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Abstract. We have used the Nobeyama Millimeter Array (NMA) to carry out aperture synthesis observations of the $J = 5{-}4$ ground state rotational transition of FeO molecule at 153.135273 GHz towards the galactic center HII region Sagittarius B2 Main (Sgr B2 M). We confirm the detection of this line in absorption with the IRAM 30-m telescope by Walmsley et al. (2002). Due to the higher angular resolution ($6''.5 \times 3''.0$) of our NMA observations, we were able to show that the absorption has a broader line width and a deeper apparent optical depth toward the central $9''.2 \times 8''.0$ area around the ultra-compact (UC) HII regions. This suggests a higher column density of FeO towards the UCHII regions associated with Sgr B2 M than along adjacent lines of sight sampled with the IRAM 30-m telescope. Our results will be a crucial step toward understanding not only the chemistry of iron-bearing species in the interstellar medium, but also the degree of depletion of heavy elements.

Key words. astrochemistry – ISM: abundances – HII regions – molecules – individual: Sagittarius B2 Main – techniques: interferometric

1. Introduction

The fate of refractory elements in molecular clouds represents a considerable puzzle. It is known that the refractory elements thought to be the essential constituents of interstellar dust particles are depleted (underabundant relative to solar abundances) in the diffuse interstellar medium (e.g. Savage & Sembach 1996). This depletion appears to increase with increasing mean density along the line of sight and in fact iron is depleted by more than two orders of magnitude in cool disk clouds. This already requires an extremely efficient mechanism to allow less than one percent of the available element to exist in the gas phase.

In molecular clouds however, there have been many searches for species containing refractory elements such as Mg, Fe, Ca, Si. With the exception of the case of silicon, these have been without success (e.g. Turner 1991) and the abundances found for the most abundant Si-containing molecule SiO has been several orders of magnitude below the Si solar abundance (see e.g. Ziurys et al. 1989). Thus silicon appears in most circumstances to be highly depleted in molecular clouds.

In the cases where SiO has been found, it has usually been associated with outflows from young stars or in more general in regions which one believes have recently undergone an interstellar shock. One such region (see Flower et al. 1995 as well as Martin-Pintado et al. 2000 for another interpretation) is the shocked layer seen in absorption towards Sagittarius B2 Main (Sgr B2 M) where extremely hot gas is observed (see Hüttemeister et al. 1995; Comito et al. 2003) as well as relatively abundant SiO (Peng et al. 1995; Greaves et al. 1996). One even observes ^{29}SiO along this line of sight and it thus should not have been a surprise that Walmsley et al. (2002, hereafter WBPS) were able to detect the ground state $J = 5{-}4$ ($\Omega = 4$) transition of FeO in absorption towards Sgr B2 M. They inferred an abundance ratio [FeO]/[H_2] of 3×10^{-11} and [FeO]/[SiO] of order 0.002.

The line detected by WBPS suffered from a uncertainty in spectral baseline associated with single dish position-switched observations towards a strong continuum source. In addition, results for more highly excited transitions were negative. In this paper, we present interferometric observations taken with the Nobeyama Millimeter Array (NMA) which should be free of

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the baseline problem and should allow an improved determination of the profile of the observed feature.

2. Observations

We carried out aperture synthesis observations of the FeO absorption line at 2-mm using the NMA at Nobeyama Radio Observatory[1]. The observations were made using the most compact D array configurations on 2003 January 5 and 6 and with C array on March 5 and 6. The phase tracking center was set at the position of the millimeter continuum source F in Sgr B2 M (Carlstrom & Vogel 1989: RA(B1950) = $17^{h}44^{m}10.36^{s}$ Dec(B1950) = −28°22′2.5″) and the field of view was 44″ at 153 GHz. We in practise were able to use 5 and 4 out of the 6 antennae in the D and C array observations respectively. All of the antennae are equipped with SIS receivers. We tuned the receivers to the frequency of FeO $J = 5$–4 ($\Omega = 4$) line (153.135273 GHz) to the upper side band of the Ultra Wide Band Correlator. The correlator was configured for a bandwidth of 512 MHz with 256 channels and on-line Hanning smoothing was applied. We thus obtained an effective velocity resolution of 7.83 km s^{-1} with a velocity coverage of 1002 km s^{-1}. System noise temperature (T_{sys}) in single-sideband was estimated to be ∼3500 K from the image noise level: the value of T_{sys} was one order of magnitude worse than the expected T_{sys} because the frequency was outside of the formal band limits of the NMA receivers.

We used 3C 273 as a bandpass calibrator and NRAO 530 as a phase and gain calibrator. From observations of Uranus, the flux density of NRAO 530 was measured and was stable with 3.2 Jy during the observation period. We estimate the overall flux uncertainty of ∼25% including errors caused by antenna pointing, instrumental gain variations and uncertainties in the flux measurements with Uranus. The data calibration was done using the UVPROCII software developed at the NRO and the image construction was performed using the AIPS package of NRAO. In order to flag out the data affected by atmospheric phase fluctuations, we only used data with a projected baseline length less than 4×10^4 λ. The resultant synthesized beam size with natural weighting was $6\farcs54 \times 3\farcs01$ at PA of −5.2°. The RMS noise level for our continuum emission image was 0.16 Jy $beam^{-1}$ and the image noise level for a line free channel with the 7.83 km s^{-1} resolution was typically 0.25 Jy $beam^{-1}$.

3. Results and discussion

In Fig. 1, we show the continuum emission map which we obtained towards Sgr B2 M. As one might expect, the source is marginally resolved and we estimate an integrated flux density at 153 GHz of 5.1 ± 1.0 Jy and a peak intensity of 3.5 ± 0.2 Jy $beam^{-1}$ (corresponding 9.3 K in main-beam brightness temperature, T_{MB}). This is of the same order as the flux measured by Carlstrom & Vogel (1989) at 3.4 mm (4.5 Jy) with a $5\farcs4 \times 2\farcs7$ beam. However, comparison with the single dish studies of

[1] The Nobeyama Radio Observatory is a branch of the National Astronomical Observatory, operated by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

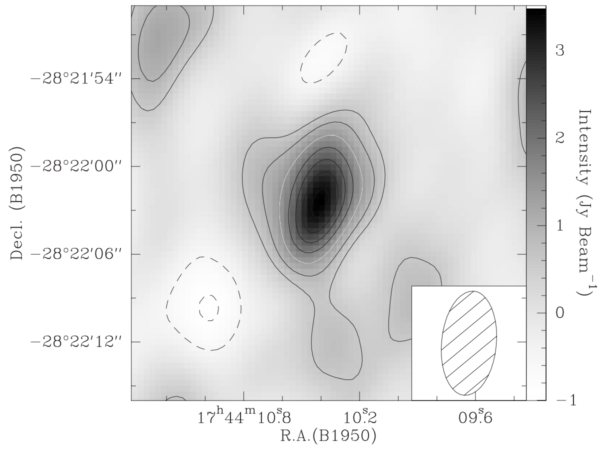

Fig. 1. Continuum emission map toward Sgr B2 M taken with the NMA. Contour levels with solid lines are 3σ intervals starting at 3σ and dashed contours are −3σ intervals starting at −3σ. The image noise level is 0.16 Jy $beam^{-1}$. The white contour indicates the region where we integrated the emission to obtain the spectrum shown in subsequent figures. The ellipse in the bottom right corner indicates the synthesized beam size.

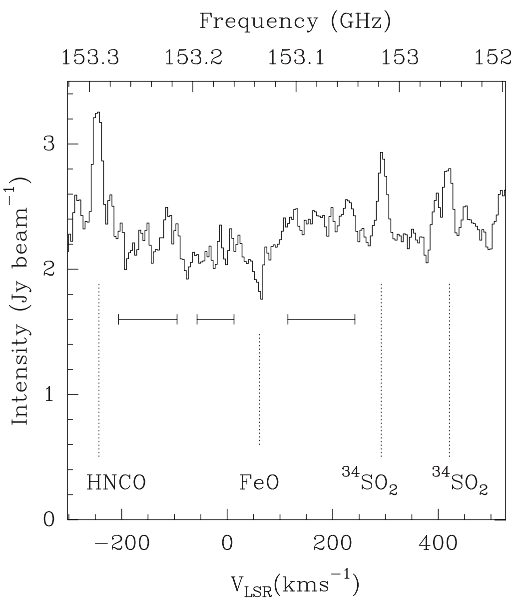

Fig. 2. Spectral line profile of Sgr B2 M at 153 GHz taken with the NMA. This spectrum was generated with image data cube by integrating the emission over the central region indicated in Fig. 1. The horizontal lines present the velocity ranges over which we estimated the continuum emission level. The vertical dotted lines indicate detected molecular lines.

Salter et al. (1989) at 90 GHz (Beam $FWHM$ ∼ 29.5″) and Gordon et al. (1993) at 230 GHz (∼11″) suggest a flux from Sgr B2 M at 153 GHz of roughly 14 Jy due to free-free emission (extrapolating from the 90 GHz data with a spectral index of −0.1) and 12 Jy due to dust emission (extrapolating from 230 GHz with a spectral index of 4). These extrapolations are likely to be rather approximate and it is notable that the sum (26 Jy) is considerably greater than the estimate of 15 Jy based on the continuum level of 3.2 K in T_{MB} (WBPS). Nevertheless, the comparison shows that the interferometer

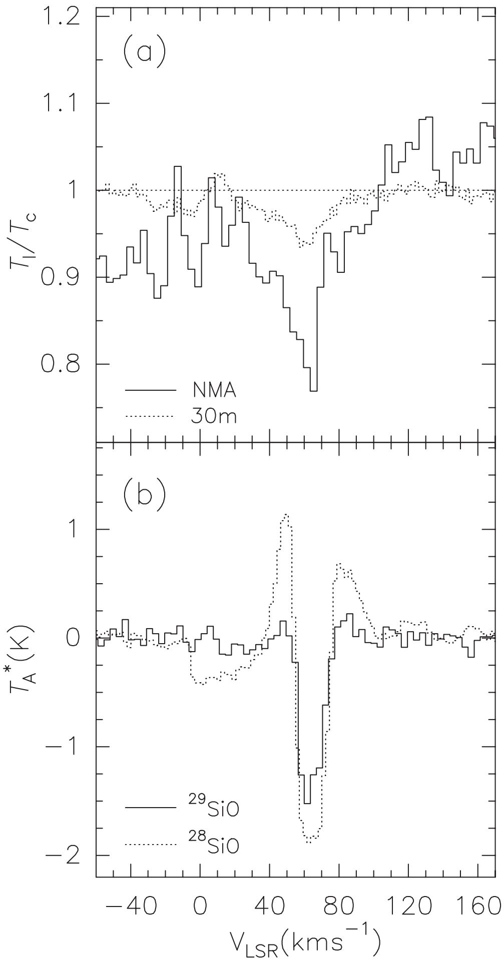

Fig. 3. a) Comparison of the line-to-continuum ratio (T_l/T_c) from the NMA observations (full; this work) with that found using the 30-m (dotted; WBPS). **b)** Spectral line profiles of $J = 2{-}1$ transition of ^{29}SiO (full) and ^{28}SiO (dotted) molecules taken with the 30-m telescope (de Vicente 1994).

measurement registers a small fraction of the continuum flux seen in the IRAM 30-m observations and hence that the continuum background against which absorption is observed differs substantially between the two measurements.

Figure 2 shows our observed spectrum from the $9''\!.2 \times 8''\!.0$ area within the half–power contour in Fig. 1. We clearly detect FeO absorption at an LSR-velocity ($V_{\rm LSR}$) of 59 km s^{-1}. We also detected emission from the $3_{22}{-}3_{13}$ and $9_{46}{-}10_{37}$ lines of $^{34}SO_2$ at 153.015 and 152.949 GHz, respectively, as well as from the $7_{17}{-}6_{16}$ line of HNCO at 153.291 GHz.

In Fig. 3, we examine more closely the FeO line profile and compare it with both the WBPS spectrum and the spectra of ^{29}SiO and ^{28}SiO lines (de Vicente 1994; Neufeld et al. 1997). The presence of wings going to $V_{\rm LSR} = 28$ km s^{-1} in the blue and to 90 km s^{-1} in the red is probable, although its signal-to-noise ratio is low. Hints of the presence of these features are seen in the 30-m spectra of WBPS but the baseline uncertainties were such that they were neglected. We conclude on the basis of the present data that these wings are likely to be real and thus that FeO absorption occurs over much of the velocity range where ^{28}SiO is detected. It is also the case however that the line-to-continuum ratio (T_l/T_c) which we measure and hence the line equivalent width (integrated T_l/T_c) is much larger than estimated by WBPS. Thus, using the frequency ranges marked in Fig. 2 to estimate the continuum level, we find an apparent optical depth T_l/T_c of order 0.2 at 60 km s^{-1} and an equivalent width integrating over velocity of 4.5 ± 0.4 km s^{-1}. By contrast, WBPS derived an equivalent width of 0.5 km s^{-1} for the narrow ($\approx$15 km s^{-1}) central feature.

We believe that this difference is partially due to the excitation temperature of the FeO (5–4) transition being comparable to the brightness of the background single dish continuum. Proof of this requires higher quality data than we presently have available. However, we note that the expected line temperature T_l along any line of sight through the source can be written:

$$T_l = \{\phi(T_{\rm ex}) - \phi(T_{\rm bb}) - T_c\}\{1 - \exp(-\tau_l)\} \qquad (1)$$

where $T_{\rm ex}$ is the line excitation temperature, $T_{\rm bb}$ is the cosmic background temperature, T_c is the continuum brightness temperature, and τ_l is the line optical depth. The quantity $\phi(T)$ is $T_0/(\exp(T_0/T) - 1)$ where T_0 is $h\nu/k$ or 7.3 K at 153 GHz. The actual observed line temperature is an average of T_l over the beam. One can expect the quantity in the left-hand brackets of the right-hand side of Eq. (1) to vary in sign due to the variation of T_c which would depend on filling factors of the continuum source(s) within the NMA and 30-m beams. In principle, both $T_{\rm ex}$ and τ_l might also significantly vary with position but it is useful initially to assume an extended absorbing layer as has been done in other analyses of Sgr B2 absorption lines (e.g. Comito et al. 2003; Ceccarelli et al. 2002).

In this case, let us assume that the observed T_c of absorption line with the 30-m is 3.2 K from WBPS, although it has considerable uncertainty as this was derived from the continuum level obtained from position-switched observations towards a strong continuum source. We thus observe an absorption line if $T_c > \phi(T_{\rm ex}) - \phi(T_{\rm bb})$ from Eq. (1). Here we note that Eq. (1) is also valid for the beam-averaged line temperature with beam-averaged T_c. On the basis of this, we obtain an upper limit of 6.7 K for the excitation temperature of the FeO (5–4) line.

Moreover, a $T_{\rm ex}$ value close to this upper limit will cause the 30-m absorption to be much weaker than that seen with the NMA (with T_c of 9.3 K). Indeed applying equation 1 both to the interferometer and single dish measurements and dividing one by the other (assuming uniform optical depth over the 30-m beam), we find that an $T_{\rm ex}$ of 6.2 K can account for a ratio of 4.8 between the line-to-continuum ratios measured with the NMA and the 30-m. However, this result is extremely sensitive to the excitation and continuum temperatures involved and we do not expect that one can account for the differences between the NMA and 30-m spectra merely due to the particular value of the excitation temperature of the observed FeO transition.

It is possible that the absorbing layer seen in FeO is mainly concentrated along the line of sight to the compact continuum sources (in other words τ_l in Eq. (1) does vary over the 30-m beam). This would clearly give rise to a higher optical depth for the NMA than for the 30-m. Then, one would expect that the FeO layer should be relatively close to the ionized gas. This would be in contrast to the situation of other tracers seen in absorption towards Sgr B2 M. NH_3 absorption (e.g.

Wilson et al. 1982; Vogel et al. 1987) for example is seen both towards Sgr B2 M and Sgr B2 North and is thought to extend over roughly 1 arcmin. We conclude that while higher angular resolution data are needed to prove this point, it is likely that the FeO optical depth and line profile vary across Sgr B2 M.

We also stress that the integrated optical depth or equivalent width derived by WBPS refers only to the narrow component seen in ^{29}SiO (see Fig. 3). The absorption seen with the NMA is over a wider velocity range than this and more comparable with the wide feature (partially in emission and partially in absorption) seen in ^{28}SiO. This reinforces the suspicion that FeO is formed in the hot relatively low density layer seen in many other tracers towards Sgr B2 M (e.g. references in de Vicente et al. 1997; Comito et al. 2003; Ceccarelli et al. 2002).

From the integrated optical depth value given above, we derive a FeO column density of 1.0×10^{13} cm^{-2} for an assumed excitation temperature of 3 K. On the other hand, with the inferred excitation temperature of 6.2 K, the integrated optical depth using Eq. (1) becomes 6.4 km s^{-1} and the column density 2.5×10^{13} cm^{-2}. With an "educated guess" for the H_2 column density of 3×10^{22} cm^{-2} (see e.g. Flower et al. 1995), we derive [FeO]/[H_2] between 3×10^{-10} and 8×10^{-10} which are higher than reported in WBPS (3×10^{-11}).

The SiO column density, which is perhaps a more reliable comparison standard, is at least 5×10^{14} cm^{-2} (Peng et al. 1995) corresponding to [FeO]/[SiO] between 0.02 and 0.05. However, we note again that this is based on the ^{29}SiO (2–1) profile and as we see from Fig. 3, this does not cover the velocity range seen in FeO and thus the SiO column is a lower limit. High resolution SiO measurements would be useful in clarifying this question

Finally, the importance of these results is that we are seeing the products of erosion of refractory grains in shocks close to the Sgr B2 M HII region. Tentative calculations based on the sputtering yield results of May et al. (2000) (Pineau des Forêts, priv. comm.) show that while Si naturally forms SiO in post–shock gas, iron remains mainly atomic. This naturally explains a large [SiO]/[FeO] abundance ratio but quantitatively how large the SiO and FeO abundances should be is very uncertain. It would clearly be extremely useful in this regard to detect other iron–bearing molecules in the Sgr B2 M absorbing layer (de Vicente 1994; Neufeld et al. 1997; Ceccarelli et al. 2002).

4. Conclusions

The main result of this study is that while we confirm the identification of the 153.135273 GHz absorption seen towards Sgr B2 M with the $J = 5{-}4$ ground state transition of FeO, we found using the NMA both a higher line-to-continuum ratio and a higher line width than seen by WBPS with the IRAM 30-m. A consequence of this is that the foreground FeO column density is apparently an order of magnitude higher than claimed by WBPS. This result is somewhat dependent on assumptions about the FeO level populations but it suggests a higher FeO column density along the line of sight to the UCHII regions in Sgr B2 M than in the more extended region sampled by the 30-m. Testing this requires obtaining higher quality higher angular resolution data both for FeO and SiO. If correct, however, it suggests that the shocks or other processes responsible for the ejection of a small amount of iron into the gas phase are caused by the stars associated with Sgr B2 M itself.

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