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Letter to the Editor

Interstellar ^{36}S: a probe of s-process nucleosynthesis*

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Abstract. The first detection of a ^{36}S-bearing molecule in interstellar space is reported. The J=2−1 and 3−2 transitions of C^{36}S have been observed toward eight Galactic molecular hot cores. From a comparison with other optically thin isotopic species of CS, the abundance ratio of ^{34}S/^{36}S is 115(±17). This is smaller than the solar system ratio of 200 and supports the idea that ^{36}S is, unlike the other stable sulfur isotopes, a purely secondary nucleus that is produced by s-process nucleosynthesis in massive stars.

Key words: Nuclear reactions, nucleosynthesis, abundances — ISM: abundances — ISM: molecules — Galaxy: abundances

1. Introduction

Sulfur possesses four stable isotopes, ^{32}S, ^{33}S, ^{34}S, and ^{36}S. In the solar system, the abundance ratios are 95.02:0.75:4.21:0.021 (Anders & Grevesse 1989). For the interstellar medium, Chin et al. (1996) determine abundance ratios of 24.4(±5.0) for ^{32}S/^{34}S, and 6.3(±1) for ^{34}S/^{33}S. While no variation in the ^{34}S/^{33}S isotope ratio is found, the ^{32}S/^{34}S ratio may increase with galactocentric radius. In the local interstellar medium (ISM) ^{32}S, ^{33}S and ^{34}S abundance ratios are not drastically different from those in the solar system. For ^{36}S, no interstellar data have been obtained so far.

^{32}S, ^{33}S, and ^{34}S are mainly primary products of oxygen burning (Woosley et al. 1973, Chin et al. 1996); however, especially the ^{34}S yield retains a substantial sensitivity to the metallicity (Woosley & Weaver 1995). ^{36}S is thought to be a purely secondary isotope produced by neutron captures on the primary sulfur seeds during helium and carbon burning (Thielemann & Arnett 1985, Langer et al. 1989). This isotope is, hence, formed in a process significally different from that of the other sulfur or CNO isotopes accessible by means of molecular spectroscopy at cm- and mm-wavelengths.

We have observed eight Galactic hot cores in two rotational lines of C^{36}S in order to determine the abundance of ^{36}S relative to other sulfur isotopes and to relate this isotopic abundance pattern to that of the local Galaxy 4.6 Gyrs ago, i.e. the solar system value.

2. Observations and results

The $J = 2 - 1$ lines of ^{13}C^{32}S, C^{34}S, and C^{36}S (95.016711 GHz, Lovas 1984), and the $J = 3 - 2$ transitions of C^{34}S and C^{36}S (142.522797 GHz, Lovas 1984; for the other line frequencies see Lovas 1992) were observed in January and June 1996 with the 12 m radiotelescope of the National Radioastronomy Observatory (NRAO) on Kitt Peak toward W3(OH), Orion-KL and W51(M). The same transitions as well als ^{13}C^{32}S $3 - 2$ were observed in March and June 1996 toward IRAS 15491−5426, IRAS 15520−5234, IRAS 16172−5028, NGC 6334A, NGC 6334B and also Orion-KL using the 15 m Swedish ESO Submillimetre Telescope SEST on La Silla. In all cases, weather conditions were good or excellent. SIS receivers were used with sideband rejections of 20 dB or better. A main-beam brightness temperature ($T_{\rm MB}$) scale was established by a chopper wheel method.

12 m NRAO observations. The FWHP beamwidth of the 12 m antenna was 65″ for the $2 - 1$ transitions, and 41″ for the 3−2 transitions. From maps of continuum sources, we estimate the pointing to be correct within 10″. The

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* Based on observations with the Swedish-ESO Submillimetre Telescope, SEST, and the 12-m radiotelescope of the National Radio Astronomical Observatory, NRAO. NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities Inc.

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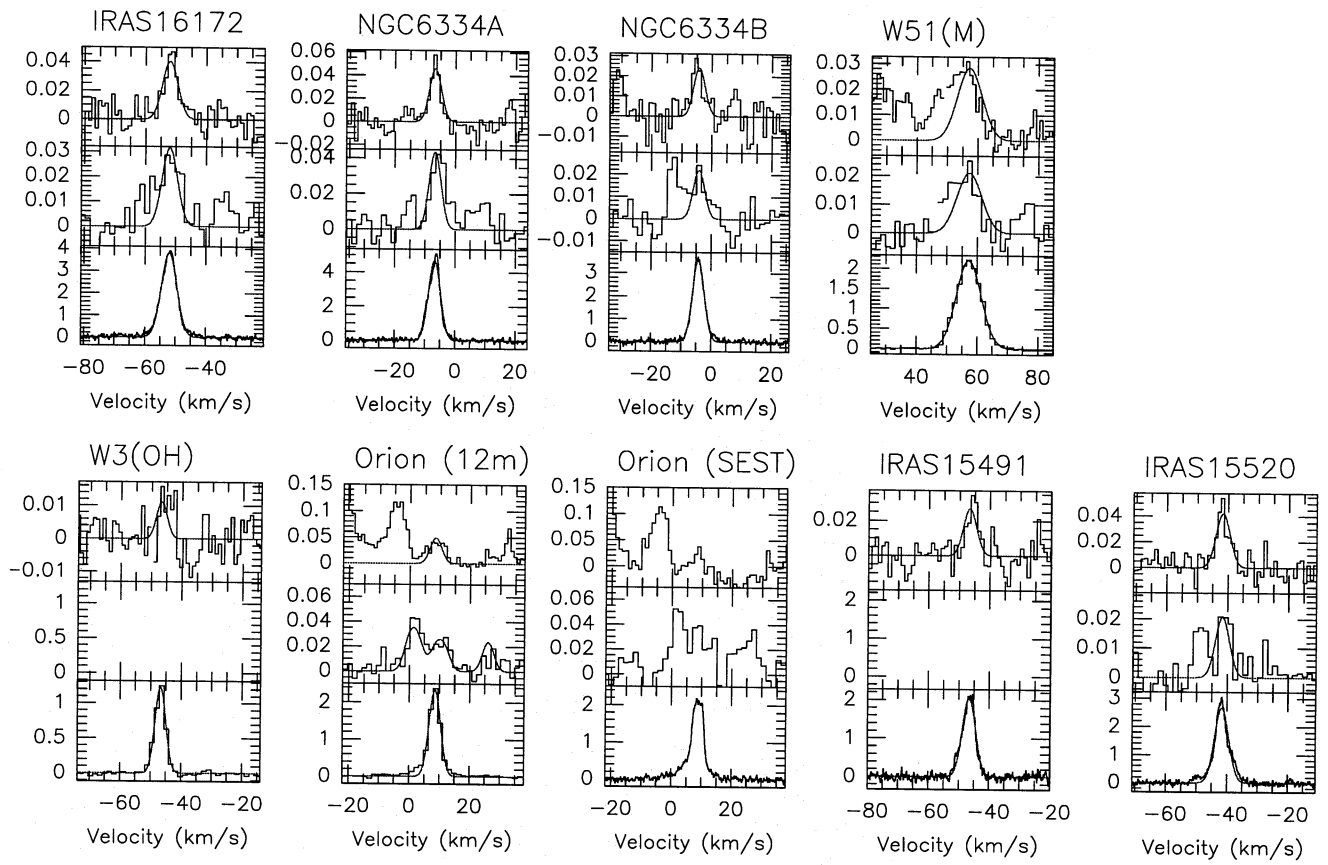

Fig. 1. The observed profiles of the lines of $C^{34}S$ 2 – 1 (lower frames), $C^{36}S$ 2 – 1 (mid frames), and $C^{36}S$ 3 – 2 (upper frames). The velocity is with respect to the Local Standard of Rest (LSR), the intensity scale is T_{MB}(K). Also shown are Gaussian fits to the lines. For Orion, a simultaneous fit of the $C^{36}S$ 2 – 1 line with a series of CH_3CCCN lines is shown.

focus was determined after sunset and after sunrise. As backends, we employed a filterbank with 2×128 contiguous channels. Each half of the filterbank was connected to one of two orthogonal polarization channels of the receiver used. The channel spacing of 500 kHz corresponds to a velocity resolution of $\sim 1.6\,\mathrm{km\,s^{-1}}$ for the $J = 2 - 1$ transitions and 1.1 $\mathrm{km\,s^{-1}}$ for the $J = 3 - 2$ transitions. All spectral lines were measured in position switch mode, the reference position being at +30′ in Right Ascension relative to the source position; 30s of integration time on the reference position were followed by 30 s on the source.

15 m SEST observations. The $J = 2 - 1$ and $3 - 2$ lines of each isotopic species were observed simultaneously with two single channel SIS receivers. At $\lambda = 3$ mm, the beam has a width of 51″, and at 2 mm, the width is 36″. The pointing was estimated to be accurate within 5″. A dual beam switch mode with reference positions offset by ±11′40″ in azimuth was employed. The backend consisted of two acousto optical spectrometers with 46 kHz channel separation. For the presentation of the $C^{36}S$ data, the resolution was reduced to 0.5 MHz.

Results. We subtracted linear baselines from all profiles. The resulting spectra of $C^{34}S$ $J = 2 - 1$ and $C^{36}S$ 2 – 1 and 3 – 2 are shown in Fig. 1. The profiles for the $C^{34}S$ 3 – 2 and the $^{13}C^{32}S$ 2 – 1 and 3 – 2 transitions have, within the noise, the same lineshape as $C^{34}S$ 2 – 1, and are therefore not displayed. The spectra toward Orion show that the calibration scale of the 12 m telescope and the SEST are, within the noise, the same. Confidence in our results is strengthened by the fact that both telescopes show the same spectral features. In the following we will use the 12 m data for Orion, which have a better signal-to-noise ratio. Spectral features at the frequency of the $J = 2 - 1$ and 3 – 2 lines of $C^{36}S$ have been detected toward all sources observed (toward W3(OH) and IRAS 15491 we only searched for the $C^{36}S$ 3 – 2 line). We have fitted Gaussians to all the lines. The results are displayed in Table 1.

3. The identification of interstellar $C^{36}S$

From Fig. 1 it is evident that close to the 2 – 1 line frequency of $C^{36}S$ there is molecular emission from another line toward some of the sources, such as Orion, IRAS 15520, NGC 6334B and possibly toward W51(M).

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Table 1. Line Parameters from Gaussian fits

Source[a]	D_{GC} (kpc)	$J-J'$	$I(C^{36}S)$ mK km s^{-1}	v^b_{LSR} km s^{-1}	$\Delta v^b_{1/2}$ km s^{-1}	$\frac{I(C^{34}S)}{I(C^{36}S)}$	$\frac{I(^{13}C^{32}S)}{I(C^{36}S)}$	$\frac{^{12}C^{32}S^c}{C^{36}S}$
W3(OH)[d]	10.4	3 – 2	49(13)	−46.8	4.2	181(49)		
Orion-KL[d]	9.0	2 – 1	∼ 83	8.5	4.5	114(50?)	46(20?)	3450(1500)
		3 – 2	233(16)			104(7)		
IRAS 15491	6.1	3 – 2	146(20)	−46.6	5.1	108(15)	57(7)	3020(370)
IRAS 15520	6.2	2 – 1	120(30)	−41.7	5.4	128(32)	68(17)	3680(920)
		3 – 2	243(20)			133(11)	77(6)	4170(320)
IRAS 16172	5.6	2 – 1	200(30)	−52.0	6.0	121(18)	60(9)	2980(450)
		3 – 2	257(30)			119(14)	64(7)	3170(350)
NGC 6334A	7.0	2 – 1	216(30)	−6.7	4.7	108(15)	52(7)	3120(420)
		3 – 2	228(30)			154(20)	83(11)	4990(660)
NGC 6334B	7.0	2 – 1	106(30)	−4.2	4.5	163(46)	76(22)	4570(1320)
		3 – 2	117(20)			156(26)	75(13)	4510(780)
W 51(M)[d]	6.5	2 – 1	214(23)	57.2	9.6	105(11)	43(5)	2420(280)
		3 – 2	290(40)			104(15)		

a) Coordinates used (B1950.0): W3(OH): $2^h23^m16\overset{s}{.}8$, $\delta_{1950} = 61°38'57''$, Orion-KL: $5^h32^m46\overset{s}{.}7$, $-5°24'24''$, IRAS 15491: $15^h49^m13\overset{s}{.}0$, $-54°26'30''$, IRAS 15520: $15^h52^m00\overset{s}{.}1$, $-52°34'26''$, IRAS 16172: $16^h17^m13\overset{s}{.}3$, $-50°28'14''$, NGC 6334A: $17^h17^m32\overset{s}{.}0$, $-35°44'05''$, NGC 6334B: $17^h17^m34\overset{s}{.}0$, $-35°42'08''$, and W51(M): $19^h21^m26\overset{s}{.}4$, $14°24'42''$; b) v_{LSR} and $\Delta v_{1/2}$ have been fixed in the fit using the values determined from $C^{34}S$ 2 – 1. c) see text; d) measured with the 12 m telescope

The 3 – 2 line appears to be less contaminated except toward Orion and W51(M). It is known that chemically younger molecular clouds such as Orion tend to have a more complex chemistry than older clouds where mainly simple molecules are observed (Helmich et al. 1994). This can explain the diffences in line blending.

Close to the $C^{36}S$ 2 – 1 transition there are several K lines of the $J = 23 - 22$ transition of CH_3C_3N (methyl cyanoacetylene; Lovas 1984). This symmetric top molecule has been previously detected toward TMC-1 (Broten et al. 1984). Assuming that the population of the corresponding levels can be described by a Boltzmann law with a kinetic temperature of 90 K (derived from the very similar CH_3CN, Cummins et al. 1983) and using the line strengths and level energies from Lovas (1984), we made a Gaussian fit fixing the estimated relative intensities of the CH_3C_3N lines for Orion, where line contamination is worst. The resulting estimate for the intensity of the $C^{36}S$ 2 – 1 line is given in Table 1.

The only line in the Lovas (1984) line catalog potentially contaminating the 3 – 2 line of $C^{36}S$ is a transition of CH_2CHCN (vinyl cyanide; $\nu = 142.527$ GHz) displaced by 4.5 MHz (9.4 km s^{-1}) from $C^{36}S$. Vinyl cyanide is known to be abundant in Orion but probably not in massive star forming regions with an "older" chemistry. The frequency separation is sufficiently high for most of the soures investigated to separate it clearly from the $C^{36}S$ emission.

We have further evidence that our identification of $C^{36}S$ is indeed correct. As it is expected for the optical thin case, the $(3-2)/(2-1)$ line ratios are similar for each of the optically thin species, including $C^{36}S$. Also there is no large variation of the line ratios between different isotopomers of a given transition for different sources. We conclude that our identification of $C^{36}S$ is justified. The line parameters are, however, best determined in sources with an "old" chemical composition (i.e. less complex molecules), such as IRAS 16172, NGC 6334A, and IRAS 15520.

4. The isotopic abundances of sulfur

We concentrate here on the $^{34}S/^{36}S$ abundance ratio since $^{12}C^{32}S$ lines tend to be moderately optically thick in Galactic star-forming regions (e.g. Frerking et al. 1980, Linke & Goldsmith 1980, Chin et al. 1996); $^{13}C^{32}S$ would involve a double isotope ratio and $C^{33}S$ is less easy to interpret due to its hyperfine structure. There is only a slight Galactic gradient in the $^{32}S/^{34}S$ abundance ratio from the data of Chin (1995) and Chin et al. (1996).

Since $C^{34}S$ and $C^{36}S$ are most probably both optically thin and since both have very similar molecular constants and were measured with the same telescopes we can assume that the ratio of integrated intensities (see Table 1) for a given rotational transition equals the respective abundance ratio. From the data in Table 1, we obtain a weighted mean abundance ratio of $^{34}S/^{36}S$=115(±17). The standard deviation given is the square root of the weighted average variance of the data (Bevington & Robinson 1992). Since we cannot exclude, at the present time, that part of the scatter in the data is caused by a Galactic gradient or by less systematic variations from source to source, we believe that this reflects the uncertainties better than the standard deviation of the weighted mean. The unweighted mean is 128(±25). The

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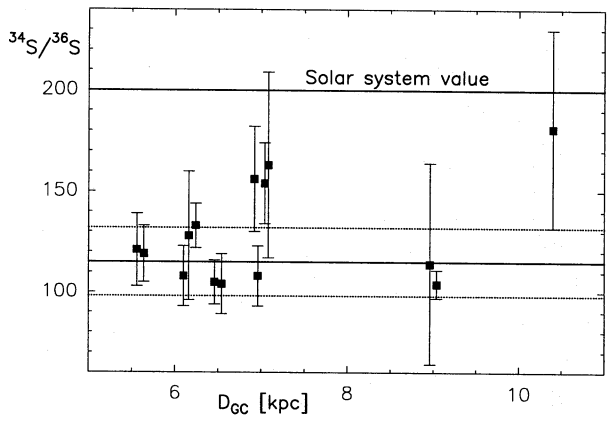

Fig. 2. The derived $^{34}S/^{36}S$ abundance ratios from the $2-1$ and $3-2$ lines as a function of the galactocentric distance. The thick and the dashed lines show the weighted mean of the measurements and the standard deviation of the data. Also shown is the solar system value of 200.

interstellar value of $^{34}S/^{36}S$ is considerably smaller than the solar system ratio of 200 (see Fig. 2). There is no systematic difference between the ratios obtained from the $2-1$ and $3-2$ lines. Due to the scatter of our data and the narrow range in galactocentric distances it is premature to discuss a Galactic abundance gradient. Using

$$\frac{^{32}S}{^{36}S} = \frac{I(^{13}C^{32}S)}{I(C^{36}S)} \frac{^{12}C}{^{13}C} \quad (1)$$

and the $^{12}C/^{13}C$ relation with galactocentric radius from Wilson & Rood (1994), we obtain as the weighted mean value from our data $^{32}S/^{36}S$=3280(±760). Also for these isotopes, the interstellar ratio is smaller than the solar system value (4520).

According to the metallicity dependent yields of ^{34}S in massive stars (Woosley & Weaver 1995), this isotope, which is produced during oxygen burning, has a character intermediate to primary and secondary isotopes. ^{36}S, on the other side, is produced as a purely secondary isotope during s-process nucleosynthesis in massive stars, predominantly in helium and carbon burning (Thielemann & Arnett 1985, Langer et al. 1989), with a possible (also secondary) contribution from AGB stars. Only a small fraction of the produced ^{36}S is destroyed in later burning phases and during the supernova explosion (S.E. Woosley, priv. comm.). According to the comprehensive massive star models of Woosley & Weaver (1995), the ratio of the production factors (i.e. output vs. input) of ^{34}S over ^{36}S in $15-25\,M_\odot$ stellar models drops roughly from 10 to 1 when the stellar initial metallicity is increased from $Z_\odot/10$ to $Z_\odot$.

A larger solar $^{34}S/^{36}S$ ratio than the corresponding present ISM value is thus in agreement with stellar ^{36}S yields increasing with time and simultaneously constant ^{34}S yields during Galactic evolution, i.e. a larger ISM value 4.6 Gyr ago compared to today. In fact, a similar trend is found in two other isotope ratios which are clearly primary vs. secondary, namely for $^{12}C/^{13}C$ ($\odot$: 89, local ISM: 70) and $^{16}O/^{17}O$ ($\odot$: 2700, local ISM: 1900; cf. Henkel et al. 1995). This analogy suggests a positive Galactic $^{34}S/^{36}S$ gradient, similar to those observed for the mentioned carbon and oxygen isotope ratios. This can be confirmed or rejected by observations of $C^{36}S$ and $C^{34}S$ in sources covering a larger range of galactocentric radii.

5. Conclusions

For the first time we have detected a molecule containing ^{36}S in space. $C^{36}S$ could be measured in two rotational transitions and toward eight molecular hot cores. The interstellar $^{34}S/^{36}S$ abundance ratio of 115(±17) is lower than in the solar system (200).

This is in agreement with the idea that ^{36}S is synthesized as a secondary isotope by s-process nucleosynthesis in massive stars.

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