A&A 381, L33–L36 (2002)
DOI: 10.1051/0004-6361:20011603
© ESO 2002

Astronomy & Astrophysics

Possible evidence for shocks in hot cores

J. Hatchell[1] and S. Viti[2]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Department of Physics & Astronomy, University College London, London WC1E 6BT, UK

Received 22 October 2001 / Accepted 12 November 2001

Abstract. The NS/CS ratio can be used to test if shocks or thermal evaporation remove grain ices during massive star formation. The two scenarios lead to differences in the subsequent chemistry: in particular, timescales are shorter if shocks are present. We have measured NS/CS ratios in six hot core sources through observation of high excitation NS, $N^{34}S$, $C^{34}S$ and $C^{33}S$ with the JCMT. The NS/CS ratios we find are low, 0.02–0.05, and surprisingly consistent between sources. Comparing with the models of Viti et al. (2001), these values rule out the standard assumption of instantaneous thermal evaporation, and favour a scenario in which hot cores are shocked at an early stage with all grain mantles evaporating instantaneously.

Key words. stars: formation – molecular processes – ISM: abundances – HII regions – ISM: molecules

1. Introduction

The birth of a massive star strongly affects the chemistry in its environment, producing “hot cores” – compact clumps of high density and temperature – which have a rich molecular chemistry that is evidence for the evaporation of ices from dust grains. Hot cores are among our best laboratories for interstellar chemistry because the high column densities mean that less abundant species are detectable. But the process that removes the ices from the grains is still uncertain: is it thermal evaporation or shocks? The subsequent chemical evolution, in particular the timescales involved, depends on the answer to this vital question.

Fast shocks (>40 $\mathrm{km\,s^{-1}}$) which would destroy molecules are ruled out by the grain chemistry in hot cores (e.g. Millar et al. 1997) but it is certainly possible that a slow shock could propagate through a hot core before or during its warming up phase, removing the grain mantles. Evidence for shocks in the form of molecular outflows appear at an early stage of high mass protostellar evolution (Cesaroni et al. 1999; Beuther et al. 2001). The order of onset of hydrogen burning, outflows, and reaching the ZAMS in high mass SFR is unknown, so a core could be shocked before or during the thermal heating stage.

Viti et al. (2001) have investigated whether it is possible to infer if and when a shock through a hot core occurs by the use of chemical models. Their models cover a variety of hot core scenarios taking into consideration different ages and masses of the embedded star. In fact, the passage of the shock is only one of the many variable parameters the models use; in addition, they also assume various time dependences of grain temperatures and evaporation (as in Viti & Williams 1999) leading to chemical differentiation for both shocked and non-shocked cores. They find that, as in previous work (Hatchell et al. 1998), the fractional abundances of various sulphur–bearing species is quite sensitive to the influence from the environment. In particular, they find that NS/CS ratios can be used as shock tracers.

To investigate whether hot cores are shocked or not, we have measured NS/CS in a sample of hot core sources with high column densities and clear evidence for grain mantle evaporation (see Table 1). We chose sources expected to span a range of different evolutionary stages: spectral signatures of collapse in W51 suggest that at least some of the sources are very young (Zhang & Ho 1997).

2. Observations and results

Results for G34.26+0.15 in $C^{33}S$, $C^{34}S$ and NS were taken from Macdonald et al. (1996) and Hatchell et al. (1998). All other observations were made in April and July 2001 with the JCMT receiver RxB3 in single sideband mode, 500 MHz bandwidth, 0.55 km $\mathrm{s^{-1}}$ channel width, with integration times from 10–90 min and system temperatures of 500–700 K. The lines observed were: NS at 346.3301/2 GHz; $C^{33}S$ at 340.0526/7 GHz and $N^{34}S$ at 340.058/9 GHz (observed in one setting), and $C^{34}S$ at 337.3967 GHz. Line parameters were taken from the JPL (`http://spec.jpl.nasa.gov`) and Köln (`http://www.ph1.uni-koeln.de/vorhersagen/`)

Send offprint requests to: J. Hatchell,
e-mail: `hatchell@mpifr-bonn.mpg.de`

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20011603

Table 1. Observed source list with positions and velocities.

Object	RA (2000) [h m s]	Dec (2000) [° ′ ″]	$v_{\rm LSR}$ km s^{1}	ref.
W31C	18 10 28.6	−19 55 56	−3	1
W51e1e8	19 23 43.8	+14 30 26	+60	2
W51 N dust	19 23 39.9	+14 31 08	+60	2
DR21OH mm	20 39 01.1	+42 22 49	−2	3
W75N	20 38 36.1	+42 37 34	+7	4
G34.26+0.15	18 53 18.5	+01 14 58	+58	5

References: 1) Olmi & Cesaroni (1999); 2) Zhang et al. (1998); 3) Mangum et al. (1993); 4) Hot core status unconfirmed but clearly a massive star forming region with high column densities – Shepherd (2001); 5) Macdonald et al. (1996).

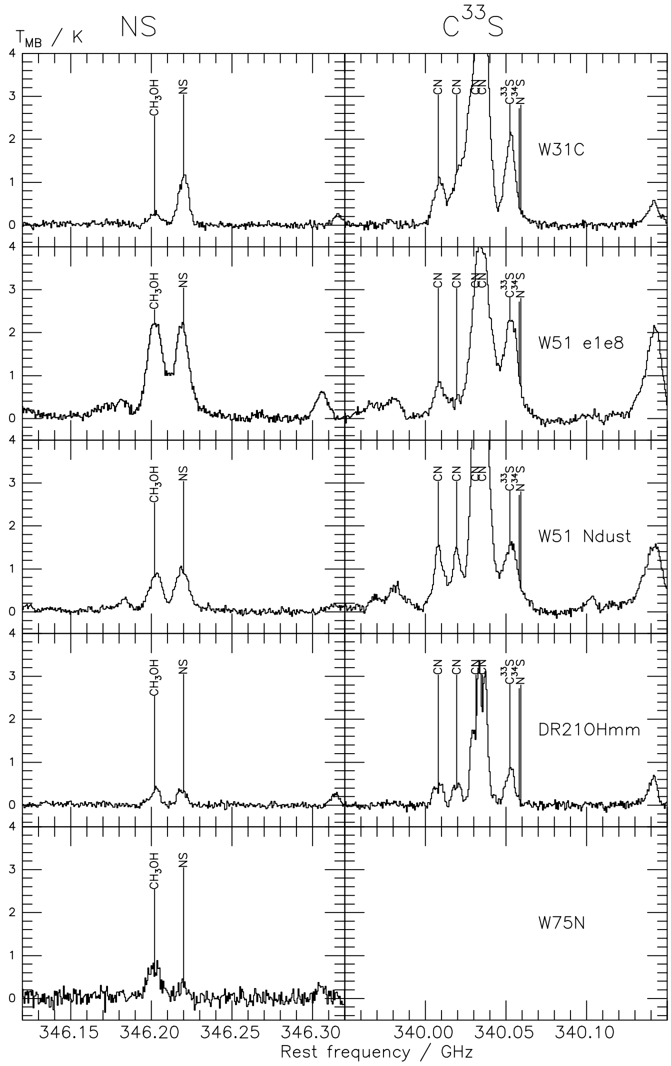

Fig. 1. NS and C^{33}S spectra.

molecular spectroscopy databases. The beam *FWHM* is 14″ at these frequencies. Calibration was checked by observation of spectral line standard sources.

3. Results and analysis

Spectra of NS and C^{33}S/N^{34}S are displayed in Fig. 1. The additional lines visible in the bands are: in the NS band, CH$_3$OH $J_{\rm K+,K-} = 5_{4,2}$–$6_{3,2}$ and $J_{\rm K+,K-} = 5_{4,2}$–$6_{3,2}$ 346.2033/40 GHz; and in the C^{33}S band, CN $J = 3$–2 at 340.008/020/032/035 GHz. Data reduction and analysis were carried out using SPECX initially and then CLASS. After calibration in which all spectra were corrected for the main beam efficiency $\eta_{\rm MB} = 0.63$, and linear baseline removal, the lines were fitted with Gaussians to extract amplitudes and integrated intensities. In the NS band where there is line blending with CH$_3$OH, both lines were fitted simultaneously. Both C^{33}S and the NS lines have nuclear hyperfine structure with splitting between the strong lines too small to be resolved and were fitted with single Gaussians. Integrated intensities are given in Table 2.

Column densities were derived assuming optically thin emission in LTE at temperatures of 20–200 K. Where hyperfine splitting was involved, the contributions from the lines were summed. Derived column densities for $T =$ 100 K are given in Table 2. Over the temperature range calculated, column densities vary between 5% smaller and a factor of 3 larger than the 100 K values given.

NS/CS ratios derived from C^{33}S and C^{34}S are given in Table 2, assuming terrestrial isotopic ratios [C^{32}S]/[C^{34}S] = 22.5, [C^{32}S]/[C^{33}S] = 125. (These isotopic ratios are also consistent with what has been observed in IRC+10216; Kahane et al. 1988.) Ratios are given for $T = 100$ K but are insensitive to T: NS/CS increases by at most 12% over the 100 K value between 20–200 K. The NS/CS ratios derived from C^{33}S are more reliable than those for C^{34}S. C^{34}S has significant optical depth so NS/CS ratios derived from C^{34}S are upper limits. The NS/CS ratio is consistently within the range 0.02–0.05.

These values are lower than previously derived NS/CS ratios of ∼0.1 for hot core sources (Hatchell et al. 1998) because previous ratios were determined using optically thick C^{34}S lines.

How reliable are these ratios? First we consider the calibration. The quoted uncertainties in Table 2 are from the Gaussian fitting and do not take into account calibration uncertainties (except for G34.26+0.15). With all observations close in frequency and with the same receiver, and calibration checked on standard sources, we would expect a relative calibration uncertainty of ∼10%.

Secondly, is the excitation likely to be subthermal, in which case by assuming LTE we will underestimate the true molecular column density? The critical densities of the transitions observed are $>10^6$ cm^{-3}, compared with densities in hot cores which reach 10^8 cm^{-3}, so thermal excitation is a reasonable assumption in these sources.

A further potential source of uncertainty in the NS/CS ratios is optical depth in the N^{32}S line but we can limit this through an upper limit on the N^{34}S line triplet, which lies in the wing of the C^{33}S line with 6–7 MHz between line centres. By fitting the two lines simultaneously we obtain

Table 2. Integrated line intensities, column densities assuming LTE at 100 K, and NS/CS ratios at 100 K calculated from $C^{33}S$ and $C^{34}S$.

Source	$\int T^*_{\rm MB}\,{\rm d}v$ / K km s^{-1}			$N_{\rm mol}\times10^{13}$ cm^{-2}			NS/CS	
	NS	$C^{34}S$	$C^{33}S$	NS	$C^{34}S$	$C^{33}S$	$C^{34}S$	$C^{33}S$
W31C	7.7 ± 0.1	37.2 ± 0.7	15.4 ± 0.5	16 ± 0.2	11.3 ± 0.2	4.8 ± 0.2	0.062 ± 0.002	0.026 ± 0.001
W51e1e8	22.2 ± 0.9	43.0 ± 0.5	24.2 ± 0.5	45 ± 2	13.0 ± 0.1	7.5 ± 0.2	0.155 ± 0.006	0.048 ± 0.002
W51 N dust	9.6 ± 0.4	18.9 ± 0.8	17.8 ± 0.4	20 ± 1	5.7 ± 0.3	5.5 ± 0.1	0.152 ± 0.010	0.028 ± 0.001
DR21OH mm	2.1 ± 0.2	1.6 ± 0.5	5.1 ± 0.2	4.3 ± 0.5	4.7 ± 0.2	1.6 ± 0.1	0.041 ± 0.005	0.021 ± 0.002
W75N	1.7 ± 0.4	11.1 ± 0.7	–	3.5 ± 0.8	3.4 ± 0.2	–	0.046 ± 0.010	–
G34.26+0.15$^{(1)}$	13.8 ± 4.1	23.0 ± 6.9	20.5 ± 6.2	28 ± 8	7.0 ± 2.0	6.4 ± 1.9	0.180 ± 0.077	0.036 ± 0.015

(1) Uncertainties on G34.26+0.15 line integrated intensities and column densities are assumed to be 30% calibration uncertainties.

Table 3. $N^{32}S$ line intensity, $N^{34}S$ line intensity upper limits, and limits on optical depth in $N^{32}S$.

Source	$T_{\rm MB}(N^{32}S)$	$T_{\rm MB}(N^{34}S)$ 3σ limit	$\tau(N^{32}S)$
W31C	1.15	≤0.23	≤1.5
W51e1e8	2.05	≤0.34	≤1
W51 N dust	0.95	≤0.34	≤3
DR21OH mm	0.31	≤0.21	≤6
W75N	–	–	–
G34.26+0.15	1.9	≤0.39	≤1.5

a 3σ upper limit on the $N^{34}S$ intensity (see Table 3). The $N^{34}S$ limits are all consistent with an optical depth $\ll$1 in $N^{32}S$. The highest possible $\tau(N^{32}S)$ in the 3σ limit are a few (see Table 3). Corrections to NS/CS for $N^{32}S$ optical depth are at most a factor of 2 increase, possibly 3.5 in DR21OH mm where the emission is weaker.

An additional uncertainty in the NS/CS ratios arises if NS and $C^{33}S$ trace different parts of the source. We minimise this by observing transitions with very similar excitation requirements. A check is consistency in line widths and velocities between NS and CS. For W75N, W31C and DR21OH mm, these were consistent (within the 3σ uncertainties from the Gaussian fits). In W51e1e8 and W51 N dust the $C^{33}S$ lines appear redshifted by 2–2.5 km s^{-1} compared to NS (the linewidths are $\sim$10 km s^{-1}). W51e1e8 shows the signature of infall (Zhang & Ho 1997) and here the NS velocity matches the cloud systemic velocity whereas the $C^{33}S$ is redshifted to match the NH_3 infalling absorption component. It could be that the column density in $C^{33}S$ is sufficient for it to show blueshifted self absorption due to infall. In this case the given CS column density is underestimated by at most a factor of 2 and the NS/CS ratio could be reduced by a factor of 2, bringing it down to 0.024.

In W51 N dust, CS observations at high resolution (Zhang et al. 1998) show more than one velocity component, which they interpret as a shell. NS appears to be tracing only one of the velocity components. For this source, the given NS/CS ratio may underestimate the true ratio in this component by about a factor of 2, increasing NS/CS to 0.056.

In conclusion, we believe our estimates of NS/CS = 0.02–0.05 are good to within a factor of 2.

To exactly what region do these values apply? The observed $C^{33}S$ and NS lines trace the same hot, dense gas, with $E_{\rm U}\geq65$ K and critical densities $>10^6$ cm^{-3}. $C^{34}S$ 5–4 ($E_{\rm U}=35$ K) maps of hot core sources trace material on scales of 10–30$''$, and LVG modelling suggests similarly large source sizes in $C^{34}S$ 7–6 (Olmi & Cesaroni 1999; Cesaroni et al. 1991). Monte-Carlo radiative transfer modelling of the same CS data gives smaller $C^{34}S$ 7–6 source diameters of a few arcseconds (van der Tak, priv. comm.; van der Tak et al. 2000). The 5 times less abundant $C^{33}S$ traces higher column density material, which must therefore be from the hot core and the inner parts of the envelope on few-arcsecond scales. We assume for our analysis that the $C^{33}S$ and NS emission is dominated by the hot core; this could, of course, be tested through high resolution observations.

4. Implications

What are the implications of the measured NS/CS ratio given the chemical models of Viti et al. (2001)? In these models, gas first accretes onto grains during a cold collapse phase. The post-collapse core, consisting of icy grains plus some remnant cold gas, is heated over various timescales. Before or during the heating, a slow C-type shock may pass through the core evaporating the remaining mantles and processing the material in the gas phase.

Viti et al. (2001) found that the NS/CS ratio is particularly sensitive to the occurrence of a shock. The two main reactions involved in the production of nitrogen sulfide require HS and NH, both the products of reactions involving OH. In the "standard" scenario, where no shocks occur but the ices are assumed to evaporate from the dust instantaneously, immediately after the star has formed, the production of NS is steady with time. In the shock case scenario however NS production is "delayed" because in the hot phase, when the gas is shocked, OH is preferentially used to form water.

By comparing the observed NS/CS = 0.02–0.05 with the theoretical models we can already exclude most of the scenarios investigated: for example, the general assumption that hot cores are not shocked and ices evaporated from the dust instantaneously, immediately after the star is formed, is unlikely to be true. Time dependent evaporation with a late-time shock is also excluded. Both these scenarios imply a far higher NS/CS ratio than observed.

A ratio of ∼0.03 indicates that the cores are younger than 10^5 years. At late times the NS/CS ratio is the same for both the "standard" model and the early shock model, and significantly higher than observed. As it is unlikely that by chance all our sources have the same age, this implies that the hot cores' lifetime may be less than 10^5 years. At any given time, there are non-shocked models which are consistent with the data but the only models which fit across a range of ages require shocks. Assuming, then, that the hot cores observed span ages up to 10^5 years still maintaining a constant ratio of ∼0.03, the most likely scenario is one where the cores are shocked at an early phase and all the mantles evaporate instantaneously as a consequence of the shock.

This conclusion – particularly the timescales – depend on the exact assumptions about the chemistry and physics in hot cores in the theoretical calculations of Viti et al. (2001). However, a wide range of freezeout and evaporation scenarios were modelled and the requirement for shocks is robust in that it does not depend on the exact depletion fraction or evaporation timescales chosen. There is no other mechanism in these models that can keep the NS production low over a timescale encompassing all the observed sources. Early shocks are a simple way of meeting this criterion.

What is the source of the shocks? As grain mantle evaporation appears localised to the hot core, the simplest solution is that the shocks are connected to the formation of the embedded star. An external mechamism would also cause chemical changes outside the core, for which there is no evidence (though effects could possibly be overlooked due to lower total column density). Wide angle winds, which have been observed to exist for young massive stars on or near the main sequence (e.g. Simon et al. 1983) are good candidates for driving shocks through the whole core. Collimated outflows also provide evidence for winds, but would produce fast shocks, only shock part of the core, and have a distinct kinematical signature which is not seen in the core material, so are not a satisfactory solution. Alternatively, the core material may be shocked during the infall process.

The shock models make no assumptions about where the shocks come from, only that the shocks are relatively slow C-type shocks, with velocities around 10 to 20 $\mathrm{km\,s^{-1}}$. Shocks of higher speed would be traceable through large SiO enhancements due to sputtered grains, for which there is currently no evidence (Hatchell et al. 2000; Schilke et al. 1997). Much slower shocks are unlikely to make a significant contribution to the chemistry of hot cores. The Viti et al. models only considered the effect of the passage of a single shock; it is possible that a succession of shocks may arise, for example due to wind variation of the massive star.

5. Conclusions

We have measured NS and CS in a sample of well known hot core sources. The chosen hot cores are believed to span different evolutionary stages. We find that the NS/CS ratio is remarkably constant among the sources and it is in the range 0.02–0.05. Comparisons with the Viti et al. (2001) models already exclude most of the scenarios investigated, including the "standard" one where ices are evaporated from the dust instantaneously, immediately after the hot star has formed. The most likely scenario seems to be instead one where the hot cores are shocked at an early stage. The shock is assumed to be a slow one where sputtering of the grains does not occur. The latter scenario has also been investigated by Charnley & Kaufman (2001); they find that the low gas/solid phase CO_2 ratio in hot cores can be explained if hot cores have indeed been shocked.

A preliminary conclusion is therefore that all hot cores undergo shocks while they are forming, or soon after. In order to test this result, high resolution observations of NS and CS and other shock sensitive species are needed.

Acknowledgements. The JCMT is operated by the Joint Astronomy Centre on behalf of the PPARC, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

References

Beuther, H., Schilke, P., & Walmsley, C. M. 2001, A&A, in press

Cesaroni, R., Walmsley, C. M., Kömpe, C., & Churchwell, E. 1991, A&A, 252, 278

Cesaroni, R., Felli, M., Jenness, T., et al. 1999, A&A, 345, 949

Charnley, S. B., & Kaufman, M. J. 2000, ApJ, 529, L111

Hatchell, J., Millar, T. J., & Rodgers, S. D. 1998, A&A, 332, 695

Hatchell, J., Fuller, G. A., & Millar, T. J. 2000, A&A, 372, 281

Kahane, C., Gomez-Gonzales, J., Cernicharo, J., & Guelin, M. 1988, A&A, 190, 167

Macdonald, G. H., Gibb, A. G., Habing, R. J., & Millar, T. J. 1996, A&AS, 119, 333

Mangum, J. G., Wootten, A., & Mundy, L. G. 1993, ApJ, 388, 467

Millar, T. J., Macdonald, G. H., & Gibb, A. G., 1997, A&A, 325, 1163

Olmi, L., & Cesaroni, R. 1999, A&A, 352, 266

Schilke, P., Walmsley, C. M., Pineau Des Forêts, G., & Flower, D. R. 1997, A&A, 321, 293

Shepherd, D. S. 2001, ApJ, 546, 345

Simon, M., Felli, M., Massi, M., Cassar, L., & Fischer, J. 1983, ApJ, 266, 623

van der Tak, F. S., van Dishoeck, E. F., Evans, N. J., & Blake, G. A. 2000, ApJ, 537, 283

Viti, S., Caselli, P., Hartquist, T. W., & Williams, D. A. 2001, A&A, 370, 1017

Viti, S., & Williams, D. A. 1999, A&A, 305, 755

Zhang, Q. H., & Ho, P. T. P. 1997, ApJ, 488, 241

Zhang, Q. H., Ho, P. T. P., & Ohashi, N. 1998, ApJ, 494, 636