Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Unravelling the sulphur chemistry of AGB stars

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Abstract. There are clear differences in what sulphur molecules form in AGB circumstellar envelopes (CSEs) across chemical types. CS forms more readily in the CSEs of carbon stars, while SO and SO_2 have only been detected towards oxygen-rich stars. However, we have also discovered differences in sulphur chemistry based on the density of the CSE, as traced by mass-loss rate divided by expansion velocity. For example, the radial distribution of SO is drastically different between AGB stars with lower and higher density CSEs. H_2S can be found in high abundances towards higher density oxygen-rich stars, whereas SiS accounts for a significant portion of the circumstellar sulphur for higher density carbon stars.

Keywords. stars: AGB and post-AGB, circumstellar matter, stars: evolution

1. Introduction

Sulphur is the tenth most abundant element in the universe and its behaviour in terms of what molecules it forms has been seen to vary for different types of AGB stars. Sulphur is not synthesised in AGB stars nor in their main sequence progenitors and studies of post-AGB stars show us that sulphur is not significantly depleted onto dust during the AGB phase (Reyniers & van Winckel 2007; Waelkens *et al.* 1991), making it a good tracer of changing circumstellar chemistry across the AGB. This also means we can study sulphur-bearing molecules in AGB circumstellar envelopes (CSEs) by estimating the total sulphur abundance, based on the solar abundance.

The most common sulphur-bearing molecules found in AGB CSEs are CS, SiS, SO, SO_2 and H_2S. We conducted an APEX survey of these molecules across a range of AGB chemical types and mass-loss rates, accompanied by radiative transfer modelling (Danilovich *et al.* 2016, 2017, 2018). Combining these results with some ALMA observations from Decin *et al.* (2018), we here summarise the overarching trends.

2. Carbon-rich and S-type stars

For carbon stars, up to half the available sulphur is in the form of CS, with the other half in SiS for the higher mass-loss rate stars. For low mass-loss rate stars, we didn't detect any SiS and expect a much lower abundance if any is present at all. Notably, no SiS was detected towards any semi-regular variables in our study. The only other sulphur-bearing molecules seen to date are H_2S and organic molecules such as C_2S, C_3S (Cernicharo *et al.* 1987), and H_2CS (Agúndez *et al.* 2008), which together account for only a small portion of the available sulphur.

For S-type stars, both CS and SiS abundances seem correlated with each other and with CSE density. No H_2S, SO, or SO_2 lines were detected in our survey.

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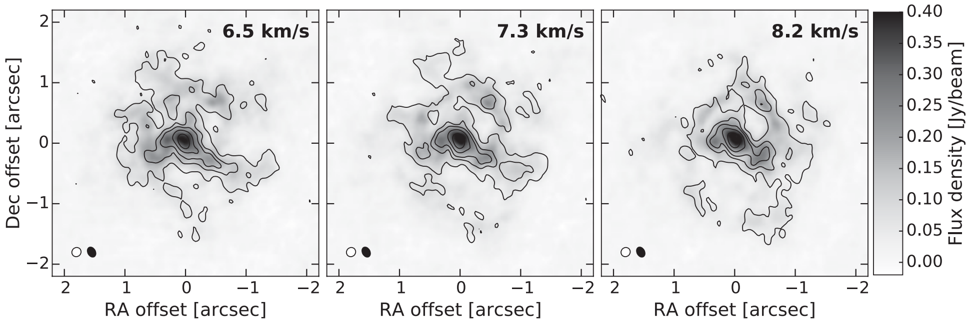

Figure 1. $SO(8_8 \rightarrow 7_7)$ (gradient, white beam) and $SO_2(20_{1,19} \rightarrow 19_{2,18})$ (contours at 1, 3, 5, 10, and 20 times the rms noise, black beam) towards R Dor, close to $v_{\rm LSR} = 7.5$.

3. Oxygen-rich stars

3.1. *Low mass-loss rate, semi-regular variable*

Here the sulphur budget is accounted for by SO and SO_2, which are both formed close to the star and occupy a similar region of the CSE. This is particularly clear when comparing ALMA observations of the two molecules, shown in Fig. 1 for R Dor.

3.2. *Low mass-loss rate, Mira variable*

The sulphur budget for these stars is mostly accounted for by SO and SO_2, both formed close to the star. However, very sensitive ALMA observations reveal additional low abundances of CS and SiS, also formed (very) close to the star. For example, we find CS and SiS abundances a couple of orders of magnitude lower than for SO for W Hya.

3.3. *Intermediate mass-loss rate, Mira variable*

In such stars, the sulphur budget is shared in a more equal way between SO, SO_2, SiS and H_2S, with lower abundances of CS (which still requires shocks to form in the oxygen-rich CSE). Unlike the lower mass-loss rate stars, SO peaks in a shell close to the peak of OH abundance (which is produced from the photodissociation of H_2O), and with a lower abundance present close to the star. This behaviour is seen in IK Tau, towards which NS has also been detected, (Velilla Prieto *et al.* 2017) but not yet fully analysed.

3.4. *High mass-loss rate, Mira variable*

For the highest mass-loss rate AGB stars (probably including the extreme OH/IR stars), the sulphur budget is dominated by H_2S, with lower abundances of SO, SO_2, SiS and CS, which are still clearly seen. An example of such a star is V1300 Aql and a deeper analysis of the high mass-loss rate OH/IR stars is coming soon (APEX observations underway).

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