S i emission in EUV spectra of late-type stars

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Summary. EUV spectra of late-type giants and supergiants observed with the 
IUE satellite show that S i accounts for strong lines which at low resolution 
cannot be distinguished from other species commonly present in dwarf stars. 
High resolution spectra of α Tau (K5III) and β Gru (M2II) show that a feature 
blended at low resolution with O i (1304 Å) is due to S i (uv 9) apparently 
pumped by the strong O i lines. Evidence for high line opacities and other 
photo-excitation processes is discussed.

1 Introduction
Observations of the K2III star α Boo obtained from a rocket flight by McKinney, Moos & 
Giles (1976) showed unusually strong O i emission at 1304 Å (uv 1). Haisch et al. (1977) 
proposed that excitation by H Lyβ to a high level in O i followed by cascade through 4s 3S i 
causes the great strength of uv 1, following a suggestion by Bowen (1947). Recent observa-
tions with the IUE satellite by Brown, Jordan & Wilson (1979), Carpenter & Wing (1979), 
Dupree et al. (1979), Dupree (1980) and Linsky & Haisch (1979) show that strong O i 
emission is common in late-type giants and supergiants.

Low resolution spectra of α Tau (K5III) and α Cet (M2III) obtained with IUE by Brown 
et al. showed a further line blended with 1304 Å. At low resolution the identification was 
ambiguous. High resolution spectra of α Tau and β Gru (M2II), recently obtained, show 
clearly that the feature is due to S i (uv 9) and suggest that pumping by O i emission occurs. 
In the present communication we discuss these and other strong lines of S i.

2 Observations and discussion
Fig. 1(a) and (b) show low resolution spectra of α Tau and β Gru, respectively. The spectrum 
of α Tau is an addition of three separate exposures of 20 min (SWP 2806), 90 min 
(SWP 4032) and 150 min (SWP 4053). Overexposed pixels were excluded from the addition. 
The flux calibration used is that by Bohlin & Snijders (1978) which is only slightly affected 
by the errors in the original intensity transfer function for the SWP camera. However an 
algorithm provided by Gondhalekar (private communication) has been used to correct our
Figure 1. Low resolution spectra of (a) ζ Tau and (b) η Gru. The spectrum of ζ Tau is an addition of three exposures of 20, 90 and 150 min. The exposure time for η Gru was 175 min. The identifications of the stronger lines are shown. Reseau marks occur at ~1200 and 1800 Å. For ζ Tau fluxes at the Earth are used as the ordinate. For η Gru, the units are IUE flux numbers combined only with the wavelength-dependent part of the absolute calibration. The lines of H Lyα, O I and Si II + S I contain some overexposed pixels and fluxes should not be derived from this figure. The figures illustrate the presence of the S I blend at ~1296 Å at low resolution.

data at the GPHOT stage. The spectrum of η Gru, obtained on 1979 October 1, is a 175-min exposure and is as provided by the IUE VILSPA processing system. A feature can be seen in both spectra at ~1296 Å, blended with the strong O I multiplet at 1304 Å.

Fig. 2(a–c) show sections from high resolution spectra of ζ Tau and η Gru, obtained on 1979 September 29 and October 7, with exposure times of 390 and 370 min respectively. In Fig. 2(a) the O I lines can be seen centred on 1302.17, 1304.86 and 1306.03 Å. All three lines show deep self-reversals and red-wing enhancements, usually associated with differential expansion of an optically thick atmosphere. The low resolution blend now appears
Figure 2. Sections of high resolution spectra of (a) α Tau and (b and c) β Gru obtained with exposure times of 390 and 370 min respectively. (a), (b) and (c) show the vicinity of Si multiplets uv 9, uv 2 and uv 1 respectively. Gaps in the spectra indicate poor data due to noise spots or proximity to the end of an order. The ordinate is IUE flux numbers. The spectrum of α Tau has been reduced from the GPHOT image. Those of β Gru are as provided by the IUE VILSPA system.
Table 1. S I (multiplet 9).

<table>
<thead>
<tr>
<th>λ (Å)</th>
<th>Transition</th>
<th>$gf$</th>
</tr>
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<tbody>
<tr>
<td>1295.66</td>
<td>$3p^4^3P - 3p^44s^3P$</td>
<td>0.60</td>
</tr>
<tr>
<td>1302.34</td>
<td>2–2</td>
<td>0.17</td>
</tr>
<tr>
<td>1296.17</td>
<td>2–1</td>
<td>0.07</td>
</tr>
<tr>
<td>1302.87</td>
<td>1–1</td>
<td>0.08</td>
</tr>
<tr>
<td>1303.89</td>
<td>0–1</td>
<td>0.13</td>
</tr>
<tr>
<td>1303.11</td>
<td>1–0</td>
<td>0.12</td>
</tr>
</tbody>
</table>

as two lines at 1295.66 and 1296.17 Å, and a further line appears at 1302.87 Å. These correspond to three components of S I (uv 9). Table 1 lists the complete multiplet (Moore 1950) and $gf$ values from Wiese, Smith & Miles (1969). Two of the S I lines at 1302.34 and 1305.89 Å lie in the strong O I wings, and have upper levels in common with the three resolved S I lines. The remaining line of the multiplet, which cannot be excited by O I, does not appear, yet should be observable if the lines are excited by collisions, whether or not they are optically thick. The spectrum of β Gru is very similar. Thus there is strong evidence that the S I lines are pumped by O I, which itself is excited by H Lyβ.

Fig. 2(b) shows the spectrum of β Gru between 1807 and 1827 Å. The commonly observed Si II lines appear at 1808.00, 1816.92 and 1817.45 Å, but the lines of S I (uv 2) at 1807.34, 1820.36 and 1826.26 Å are stronger. In α Tau the S I lines have about half the intensity of the Si II lines. Carpenter & Wing (1979) have pointed out that the S I lines are much stronger than the Si II lines in α Ori (M2Iab). Thus in low gravity stars later than mid K both Si II and S I must be taken into account when analysing low resolution spectra. An important result is that the intensities of the S I lines, which have a common upper level, depart from the ratio of 5.6:3.0:1.0 expected from the transition probabilities (Wiese et al. 1969). The ratios are close to 1:1:1 indicating a high optical depth. In α Ori the lines show self-reversal.

Fig. 2(c) shows the intersystem S I lines (uv 1) at 1900.27 and 1914.68 Å, and in β Gru. They also appear in α Tau. The intensity ratio is smaller than the value of 3.5:1 expected if the lines are optically thin, but is still greater than 1:1, suggesting $\tau \leq 1$ in these lines. The opacities of uv 2 and uv 1 will be used in further modelling. They immediately allow limits to be placed on the S I column density such that $10^{13}\text{cm}^{-2} < J\langle\text{cm}^{-2}\rangle < 10^{16}\text{cm}^{-2}$. Neither the Si III at 1892.03 Å nor the C III line at 1908.73 Å is present in either spectrum.

Lines near 1473 and 1483 Å (uv 3) have been identified as S I by several authors from low resolution spectra. Our high resolution spectrum of β Gru does show weak lines at 1474.0 and 1474.4 Å, confirming the suggestion. However, the intensity of uv 5 at 1425 and 1433 Å is substantially lower than expected from the relative intensities of uv 3 and uv 5 in the solar spectrum, where they would be excited by collisions at $T_e \sim 6000$ K. There are several possible causes for this difference; $T_e$ may be substantially lower; photo-ionization or excitation processes followed by recombination and cascades may be more important; overlying opacity may occur around 1425 Å. The higher opacity in uv 5 (by a factor of two) should not cause such a strong difference in fluxes at low resolution.

Regarding photo-ionization and excitation, it should be noted that the S I ionization edge lies at ~ 1203 Å and thus the broad H Lyα emission can excite numerous high $n$ levels, close to the ionization limit. Whether or not this effectively results in ionization depends on the density. However, in any case, cascading through the lower levels may occur selectively enhancing some lines.

One further strong line may result from high opacity in either S I (uv 5) or the O I resonance lines (uv 1). We notice that a line at ~ 1640 Å in low resolution spectra persists.
in the late-type giants and supergiants. In hotter stars and dwarf stars the 1640 Å feature is usually identified with He II + Fe II, but He II is not expected in the giants and supergiants. Fe II is difficult to exclude since it is strong in the long wavelength spectra of α Tau and β Gru, but the presence of a line at 1641.2 Å in the high resolution spectra shows that Fe II cannot be the sole contributor. Both Si and O I have intersystem lines near 1641.2 Å. The Si lines at 1641.11 and 1641.33 Å have $^3D_{1,2}$ levels in common with uv 5; the O I line at 1641.30 has an upper level in common with the strong uv 1 multiplet. It is known that the intersystem line of C I at 1994 Å can be enhanced when the C I 1656 Å multiplet has a high opacity (Jordan 1967). The presence of both these C I multiplets in α Tau and β Gru shows that such a process may be relevant. Moreover the transition probability ratios (Müller 1968; Garstang 1961) are suitable. Again the identity of a feature at low resolution may change according to the spectral type of the star.

3 Conclusions

Si lines become important in the spectra of late-type giants and supergiants, and may replace other contributors commonly present in hotter stars, having indistinguishable wavelengths at low resolution. Evidence of photo-excitation and high line opacities is present. Several line ratios can be used to determine opacities, which together with absolute fluxes will provide valuable information on the atmospheric structure.

Acknowledgments

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References