EVOLUTION OF SOUTHERN STAR-FORMING REGIONS

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Abstract. We present ISO observations of bright, high–mass southern star-forming regions with the Short Wavelength Spectrometer (SWS) and Long Wavelength Spectrometer (LWS). The selected targets show a range of pre-main sequence evolutionary phases. Whereas some objects still show interstellar ice features, the most evolved objects are coincident with ultra-compact HII regions and show strong emission lines from atomic species and polycyclic aromatic hydrocarbons (PAHs). We discuss the ISO spectra between 2.5 - 200 μm of selected southern star-forming regions in the context of their evolution.

1. Introduction

We have observed high mass star-formation regions in the southern sky, which are rather unexplored to date. The objects AFGL4176, NGC6334

IRS1, NGC3576, G327.3-0.5, G333.13-0.43 are all characterized by high infrared fluxes (> 100 Jy at 12 μm). Our aim is to study the line-of-sight conditions in order to determine their evolutionary stage. In particular, it has been suggested that the chemical composition and gas/solid state ratios are sensitive functions of age (van Dishoeck et al. 1996). The combination of the ISO data with submillimeter observations is particularly powerful, since the latter mainly probe the physics and chemistry of the envelopes, whereas ISO can constrain the denser and warmer circumstellar gas. We measured gas-phase species as well as solid-state features between 2.5 and 200 μm. Gas-phase observations allow us to measure directly the sublimation from grains and estimate the excitation temperature of the gas. The profiles of solid species can give indications about the polar and apolar character of the ices and on temperature and irradiation conditions. Further information can be obtained from atomic emission lines, silicate bands and the presence of PAH (polycyclic aromatic hydrocarbon) features. This combined information can be used to constrain the processes which determine changes in the composition and excitation of the material towards these star-forming regions. A particularly interesting question is at what stage the ultraviolet radiation from the young star starts to significantly affect its surroundings.

2. Observations

ISO SWS01 and LWS01 observations have been obtained for the objects AFGL4176, NGC6334 IRS1 and G327.3-0.5. NGC3576 was observed in SWS06 and LWS01 mode and the object G333.13-0.43 has been observed only in SWS01 mode. For most of the objects additional SWS06 (high resolution) observations are available for complementary information. The LWS observations were end-to-end grating scans from 42-197 μm with an oversampling factor of 1. For each target an off-source measurement was performed. The data were reduced using standard procedures in the IA package. Small corrections were made to match the edges of different AOT bands.

3. Results

Fig. 1 shows a comparison of 4 southern star-forming regions in the range of 4-12 μm, observed with ISO-SWS01. AFGL4176 and NGC6334 show H_2O (at 3 and 6 μm) and CO_2 ice (at 4.27 and 15.2 μm) as well as silicate bands (at 10 and 18 μm) in absorption. G327.3 -0.5 and G333.13-0.43 are apparently more evolved sources. Their spectra are dominated by atomic emission lines (such as Ar II at 6.98 μm and S III at 18.7 and 33.5 μm) and polycyclic aromatic hydrocarbons (see Figure 3), indicative of HII regions

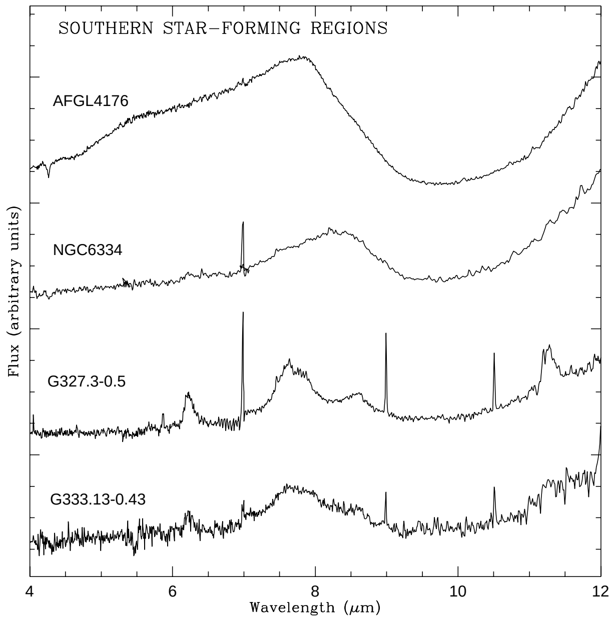

Figure 1. SWS01 spectra of bright southern star-forming regions between 4-12 μm in evolutionary sequence. Interstellar H_2O (at 6 μm) and CO_2 ice (at 4.27 μm) as well as gaseous species are seen in absorption towards the young objects AFGL4176 and NGC6334 IRS1. Compact HII regions towards G327.3 -0.5 and G333.13 -0.45 are confirmed by strong atomic emission lines and PAH features.

towards and beyond the star. The protostar NGC3576 displays CO_2 and H_2O ice, HeI lines, PAHs as well as gaseous CO and H_2O (van Dishoeck et al. 1997).

AFGL4176, also known as IRAS 13395-6153, has been previously discussed by Persi et al. (1986) and Siebenmorgen (1993). The object shows H_2O and CO_2 ice with column densities of 9.0×10^{17} cm^{-2} and 1.2×10^{17} cm^{-2}, respectively (van Dishoeck et al. 1996). Solid CO (at 4.67 μm) was not detected and only an upper limit of $< 0.5 \times 10^{17}$ cm^{-2} could be determined. The gas/solid ratios for CO_2, H_2O and CO are 0.04, 2.2 and $>$ 400, respectively (van Dishoeck et al. 1996). These ratios indicate a large fraction of high temperature gas and dust in the line-of-sight. The optical depth of the silicate band at 9.7 μm was measured to be 2.44, compared with previous measurements of 5.05 (Persi et al. 1986). This new value also indicates an A_V of only 38$\pm$ 5 mag. All these parameters constrain this object as a very young embedded star with a protostellar dust shell.

NGC6334 IRS1 is studied with ISO by various other groups in high

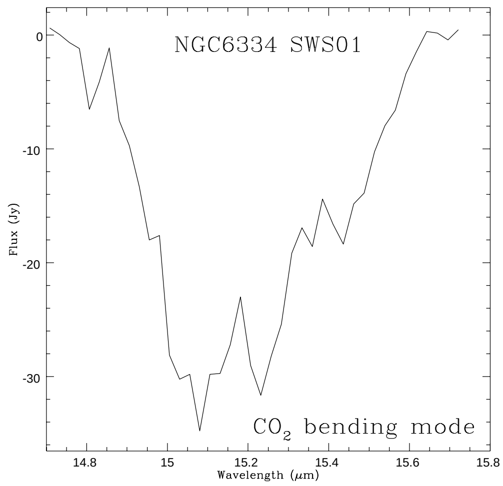

Figure 2. SWS01 spectrum of NGC6334 IRS1 showing the CO_2 bending mode at 15.2 μm. This particular profile indicates pure CO_2 grain mantle layers which can only exist below 45 K (Ehrenfreund et al. 1996, 1997; de Graauw et al. 1996)

resolution mode. We therefore restrict ourselves to the CO_2 bending mode at 15.2 μm, which displays a typical three-peak structure (see Figure 2). This specific profile was observed towards several cold dense clouds such as NGC7538 IRS9 or GL2136 (de Graauw et al. 1996) and confirms the presence of polar (water-rich) ices and apolar CO_2 ice. Apolar ices are composed of rather volatile molecules, such as CO, O_2, N_2 and CO_2. Apolar CO_2 can only exist in temperature zones far from the protostar with less than 45 K.

The rich spectrum of the protostellar source G327.3 -0.5 allows us to determine the nature of the ionizing source. Using the ratio of the S III lines at 33 and 19 μm as well as the O III lines at 88 and 52 μm we derive from comparison with Rubin et al. (1994) preliminary values for electron densities of 300–1000 cm^{-3}. The effective temperature of the exciting star illuminating the HII region towards G327.3 -0.5 is estimated to be 36,000-40,000 K using the ratio of the S III and O III lines. Theoretical models of the emission lines with the ionization program CLOUDY are currently underway in order to constrain the density and overall environment of G327.3-0.5.

4. Conclusion

The selected protostellar targets show a range of pre-main sequence evolutionary phases, see Table 1. AFGL4176 and NGC6334 show H_2O and CO_2

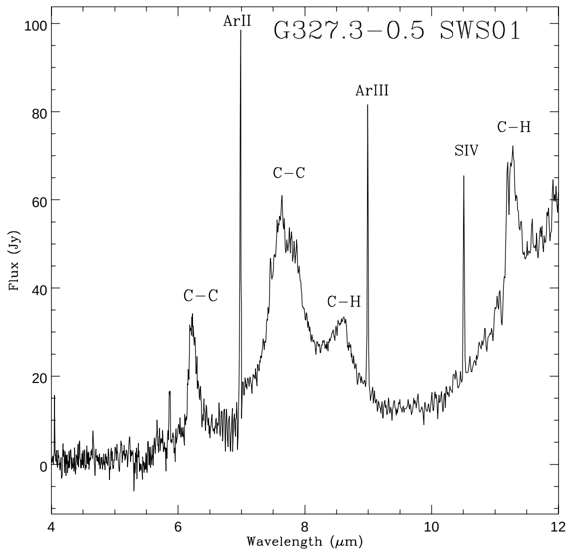

Figure 3. SWS01 spectrum of G327.3-0.5 showing the C-C stretching modes of PAHs at 6.2 and 7.7 μm, the C-H bends at 8.6 (in plane) and 11.3 μm (out of plane) as well as atomic emission lines. The corresponding ratios of the PAH emission bands are 6.2/7.7 = 0.3, 7.7/11.3 = 6.9 and 3.3/11.3 = 0.2. Similar values have been observed for other compact HII regions (see Roelfsema et al. 1996).

TABLE 1. Evolution of southern star-forming regions

Source	Ices	Gas	other features
AFGL 4176	CO_2, H_2O	CO_2, H_2O, CO	silicates
NGC 6334	CO_2, H_2O	CO_2, H_2O, CO	silicates
NGC 3576	CO_2, H_2O	CO_2, H_2O, CO	PAHs, HeI
G327.3-0.5	H_2O	H_2O	atomic lines, PAHs
G333.13-0.43	no	H_2O	atomic lines, PAHs

ice in the line-of-sight, which confirm low temperature regions below 90 and 45 K, respectively. The absence of solid CO in both objects indicates that the coldest parts of the clouds are > 30 K. Abundant gaseous CO and H_2O indicate also high temperature gas in the line-of-sight. Persi et al. (1994) describe NGC 3576 as a young massive star cluster deeply embedded in a molecular cloud. NGC3576 does show HeI lines and PAH features in addition to H_2O, CO_2 ice and gas and is placed as an intermediate object (or combination of young stellar objects) in the evolutionary sequence of our

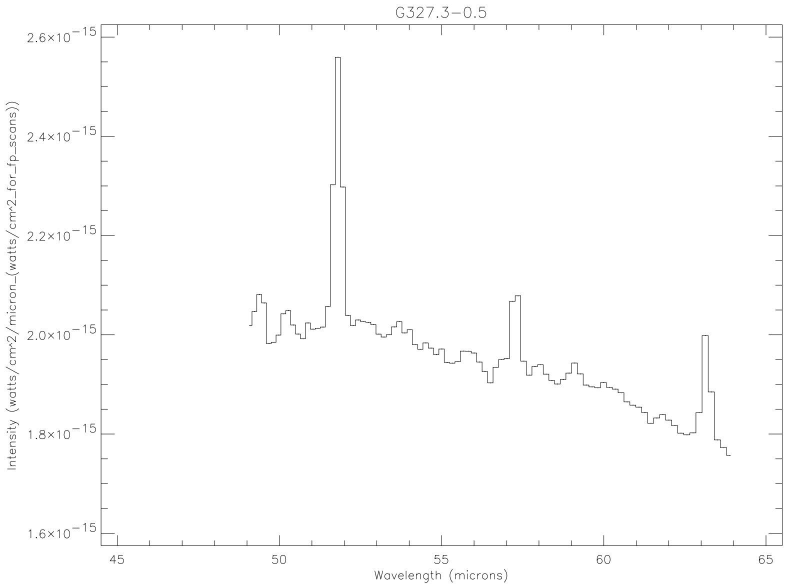

Figure 4. LWS01 spectrum of G327.3 -0.5 showing the strong atomic emission lines of O III at 52 μm, N III at 57 μm and O I at 63 μm.

sources (van Dishoeck et al. 1997). G327.3-0.5 and G333.13-0.45 show ultracompact HII regions with strong PAH emission and represent likely more evolved regions. Future work will include theoretical modelling of emission lines in the near and far-infrared and the determination of the excitation temperature for all gas-phase species. The profiles of solid state features in comparison with laboratory results will indicate temperature and irradiation conditions and the ice type (such as polar or apolar). This will complete the information needed to derive the environmental conditions and evolutionary processes in these star-forming regions.

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