AN INFRARED STUDY OF THE L1551 STAR FORMATION REGION - WHAT WE HAVE LEARNT FROM ISO AND THE PROMISE FOR FIRST

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Abstract

ISO spectroscopic observations are reported towards the well known infrared source L1551 IRS 5. The continuum spectral energy distribution has been modelled using a 2D radiative transfer model, and fitted for a central source luminosity of 50 $L_\odot$, surrounding a dense torus extending to a distance of $\sim$ 30,000 AU, which has a total (gas + dust) mass of 25 $M_\odot$. The extinction towards the outflow is estimated to be $A_v = 11$ and the mid-plane optical depth to L1551 IRS 5 to be 140. On the basis of this model, the extinction curve shows that emission at wavelengths shorter than $\sim 2\ \mu$m is due to scattered light from close to L1551 IRS 5, while at wavelengths greates than 4 μm, is seen through the full extinguishing column towards the central source.

Key words: Interstellar Medium: Star formation – Individual source: L1551 – Missions: FIRST – macros: LaTeX

1. Introduction

Lynds 1551 is one of the most intensively studied molecular outflow sources. Lying at a distance of $\sim$ 150 pc in the Taurus–Auriga dark cloud, it is associated with a 30 $L_\odot$ Class I protostar, L1551 IRS 5. This is presumed to be in a pre–T Tauri phase and the driving source of a molecular outflow, and an optical jet. The extinction, A_v, towards IRS 5 has been estimated to be $\gtrsim 150$ magnitudes. Continuum maps reveal that the dense central core is surrounded by an extended cloud. The spectral energy distribution and intensity maps of L1551 IRS 5 have been modelled in detail using radiative transfer methods in spherical and axially–symmetric geometries These suggest that a flat accretion disc or a geometrically thick torus lies inside the extended cloud. High resolution radio observations have shown evidence for a double source located at IRS 5. Other interpretations of the available data suggest a different morphology, with a binary system lying at the centre of IRS 5 whose components are separated by $\sim$ 50 AU, which is in turn surrounded by a dusty disc. Hubble Space Telescope (HST) observations suggest that there are two distinct optical jets, supporting this circumbinary interpretation, and that the central region surrounded by a torus, with a mass $\sim$ 0.1–0.3 $M_\odot$, and a radius of $\sim$ 700 AU, surrounding an $\sim$ 70 AU central cavity, which contains the double radio source. There appears to be an evacuated cavity in the torus, with a half–opening angle of about 50–55°. The axis of the molecular outflow is inclined at about 30–35° to the line of sight. In this paper, we report spectroscopic observations obtained with the ISO Long (LWS) and Short Wavelength spectrometers (SWS) towards IRS 5.

2. Observations

An ISO SWS spectrum was obtained towards IRS 5 using the S01 mode (2.4 – 45 μm, scan speed 4, resolution $\sim$ 1000–2000, integration time 6590 seconds). The SWS aperture varied from $14 \times 20'' - 17 \times 40''$ for the 2–40 μm regions respectively. The data reduction was carried out using the standard ISO analysis software ISAP v1.6 and LIA 6. Small corrections were made for fringing, and to align adjacent detector scans, but overall the standard pipeline data was of high quality. The SWS observations were made with the long dimension of the slit oriented at position angle 171° (measured anticlockwise from north) – this lies almost orthogonal to the direction of the molecular outflow.

3. Radiative transfer modelling

In order to interpret the observations in a quantitative way, we constructed a self–consistent two–dimensional (2D) radiative transfer model for L1551 IRS 5. Whereas Men′sh-

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

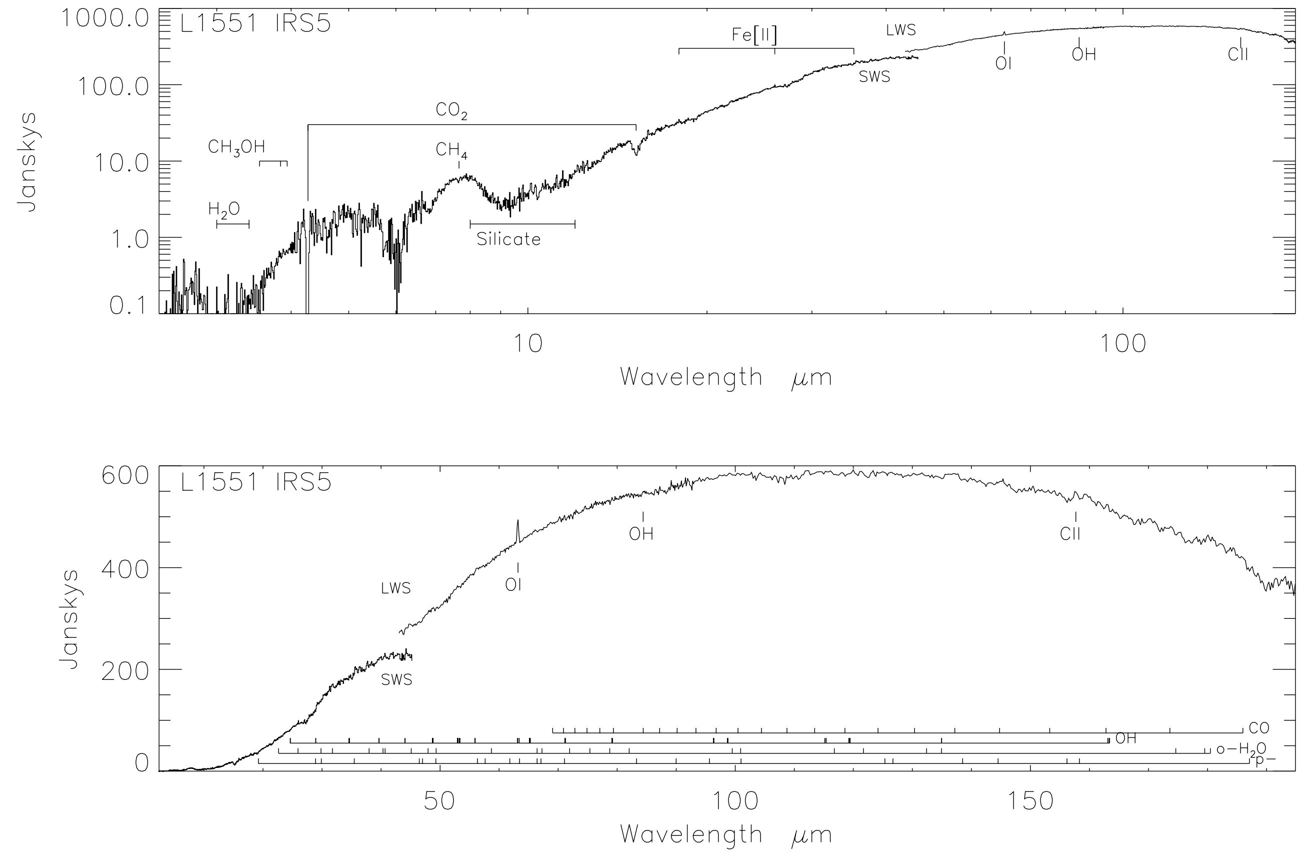

Figure 1. ISO SWS and LWS spectra of L1551 IRS-5.

chikov & Henning(1997 – MH97) have already presented a comprehensive model for this object, their calculations were affected by numerical energy conservation problems resulting from very high optical depths of the model and incomplete convergence of the iterations. The problem, which mainly affected the total luminosity of the central object and the near– to mid–IR part of the SED in the MH97 model, has now been improved (see, e.g., the model of HL Tau by Men′shchikov et al. 1999 – MHF99).

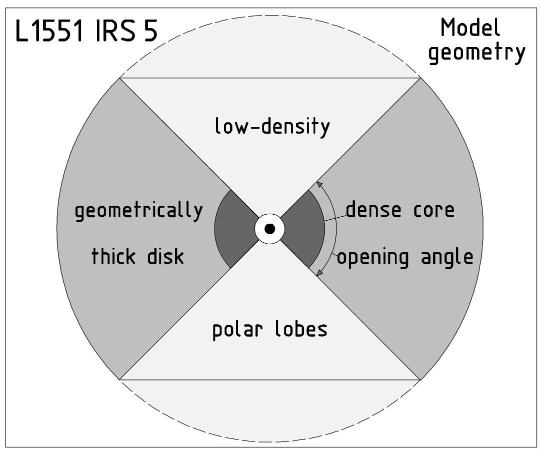

Figure 2. Geometry of the L1551 IRS 5 model.

In this paper, we have recomputed the model using the modified version of the code and the new constraints provided by the ISO and HST observations presented above. Our approach and the model are basically the same as those in MH97 and MHF99. We refer to the papers for more detailed discussion of our approach, computational method, model parameters, and ′error bars′ of the modelling.

Following MH97, we assume that the central star (or a binary) is surrounded by a dense core (with a radius of $\sim$ 100 AU), which is embedded within a much larger non–spherical envelope (outer radius of $\sim 3\,10^4$ AU). A conical cavity has been excavated by the bipolar outflow, and has a full opening angle of 90°. This axially–symmetric geometry is the same for both the core and the surrounding material, as schematically illustrated in Fig. 2.

There are three regions that make up the torus: the innermost very dense parts with a $\rho \propto r^{-1}$ density gradient, and low–density outer parts with a broken power–law (ρ = const and $\rho \propto r^{-2}$) density profile. A steep $\rho \propto \exp(-r^2)$ transition zone parts with a broken power–law (ρ = const and $\rho \propto r^{-2}$) density profile. A steep $\rho \propto \exp(-r^2)$ transition zone between them effectively forms the outer boundary of the inner dense torus at $\sim$

Table 1. Main input parameters of the IRS 5 model

Parameter	Value
Distance	160 pc
Central source luminosity	50 $L_\odot$
Stellar effective temperature	5000 K
Flared disc opening angle	90°
Viewing angle	44.5°
Torus dust melting radius	0.4 AU
Torus outer boundary	30000 AU
Torus total mass (gas+dust)	25 $M_\odot$
Density at melting radius	7.9 10^{-13} g cm^{-3}
Density at outer boundary	7.9 10^{-19} g cm^{-3}
Outflow visual A_v	11 mag
Midplane $\tau_{0.55\mu m}$	140

100 AU. Conical surfaces of the bipolar outflow cavities define the opening angle of the torus to be 90°. Dust evaporation sets the inner boundary at ≈ 0.4 AU, while the outer boundary is arbitrarily put at a sufficiently large distance of $3\,10^4$ AU. The polar outflow cones with a $\rho \propto r^{-2}$ density distribution have much lower density than the torus.

The density distributions inside the torus and in the bipolar cavities are functions of only the radial distance r from the centre, where the source of energy is located. We neglect in this model the putative binary system inside the dense core, because its semi-major axis ($\sim$ 24 AU) would be much smaller than the radius of the core. If the binary does exist, it is likely that there is a very large cavity around it, with a radius of $\sim$ 24 AU. Our modelling has shown that in the presence of such a dust–free cavity, the inner dust boundary would have a temperature of only $\sim$ 150 K, far too low to explain the observed SED of L1551 IRS 5. In fact, the near– and mid–IR fluxes would be (many) orders of magnitude less than the observed ones. Instead of assuming that the entire binary fits into the dust–free cavity, we adopt the view that a substantial amount of gas and dust exists deeper inside the core, as close as $\sim$ 0.4 AU to the central source(s) of energy.

The overall quantitative agreement of the model SED with the entire set of observations of L1551 IRS 5 is very good. The total model fluxes corrected for the beam sizes (lower points of the 'teeth' in Fig. 3 coincide well with the observed fluxes, except for those in the near IR, although the shape of the SED is still very similar to the observed one. Whereas only the lower points of the teeth are relevant, we have connected them to the adjacent continuum by straight lines, to better visualise the effect. The latter is evident everywhere, except for only the mid–IR wavelengths, where the source is very compact and most of its radiation fits into the SWS beam. Note that at millimetre waves the model predicts significantly larger *total* fluxes compared to the observed ones, indicating that the outer envelope is very extended and sufficiently massive.

4. The model

The structure of our model of L1551 IRS 5, which is very similar to that presented by MH97, is illustrated in Fig. 4. The distribution of densities and temperatures in the model were chosen to be similar to those of HL Tau (MHF99), except for the flat density area between 250 and 2000 AU which is likely to exist in IRS 5. The density structure in the inner few thousand AU is constrained by the SED, the long–wavelength intensity maps, and the submm/mm visibilities.

The compact dense toroidal core has a radius of $\sim$ 100 AU and a $\rho \propto r^{-1}$ density distribution. It is embedded into a low–density envelope with an outer radius of $3\,10^4$ AU and a broken–power–law density profile ($\rho =$ constant for 250–2000 AU and $\rho \propto r^{-2}$ for larger distances). The compact core is connected to the envelope by a segment of a Gaussian having a half–width at half–maximum of 70 AU. The boundary of the torus extends from 80 to 250 AU and is effectively truncated by the exponential at about 200 AU, very similar to the density profile of HL Tau (MHF99).

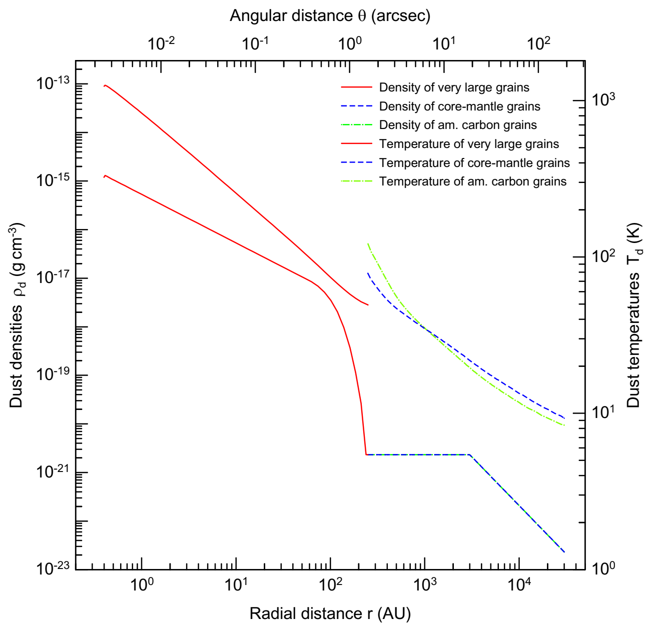

Figure 4. Density and temperature structure of the IRS 5 model.

In the absence of any reliable constraints, the conical outflow regions are assumed to have a $\rho \propto r^{-2}$ density profile which is consistent with available data. The temperature profile displays a jump at 250 AU, where the hotter normal–sized dust grains of the envelope are assumed to be coagulated into the large grains of the dense core. We refer to MH97 and MHF99 for a more detailed discussion of the density structure and of the uncertainties of our model.

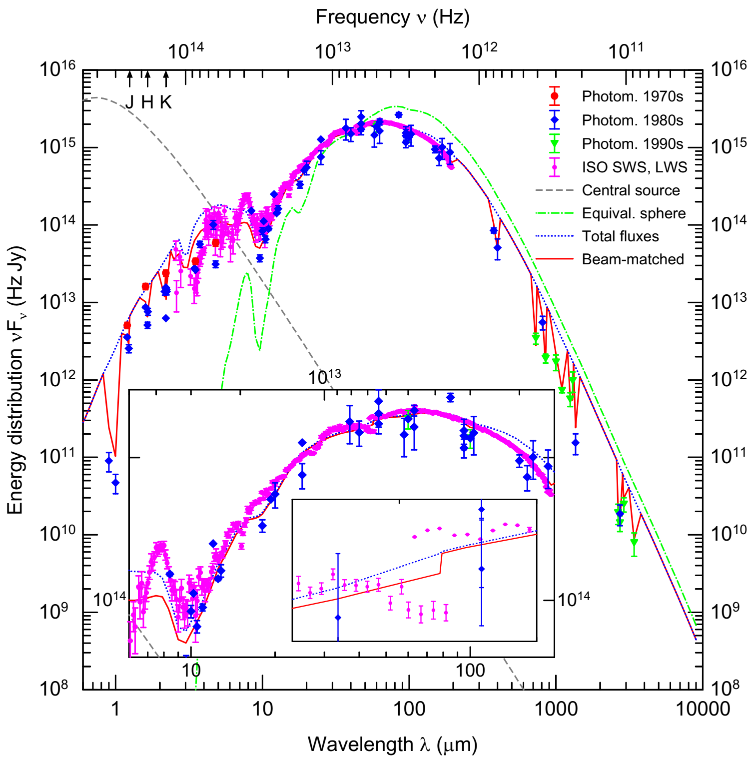

Figure 3. Comparison of the new IRS 5 model with the ISO SWS, LWS spectrum, and various, mostly ground–based, photometric points. The individual fluxes (taken from MH97) are labeled by different symbols, to distinguish between old observations (before 1980, circles), recent ones (1980–1990, diamonds), and new data (after 1990, triangles). Error bars correspond to total uncertainties of the observations. The stellar continuum (which would be observed, if there were no circummstellar dust, is also displayed. The model assumes that we observe the torus at an angle of 44.5° *(relative to its midplane). The large insert shows in more detail most of the SWS and LWS spectrophotometry (6–200 μm). The small insert displays in even greater detail the region of the ′mismatch′ between the SWS and LWS data (38–50 μm). The effect of beam sizes is the cause of the ′teeth′ in the model SED. To illustrate the influence of the bipolar outflow cavities, the SED for the equivalent spherical envelope is also shown.*

5. Conclusions

Observations have been made towards the well known infrared source L1551 IRS 5, using the LWS and SWS spectrometers on the ISO satellite, and several other near-IR telescopes. The main results of this study were:

1. The ISO LWS spectrum consists of a relatively strong continuum, superposed with a few weak lines of OI, CII and possibly OH. Emission from other species such as CO or H_2O was not detected. This might indicate that either the molecules have been destroyed, perhaps in a shock, or that the environment is unable to excite them to emit in the far and near infrared.
2. The continuum spectral energy distribution has been modelled using a 2D radiative transfer mode. The continuum is well fitted for a central source luminosity of 50 $L_\odot$, surrounded by a flared disc with an opening angle of 44.5°. The outer parts of the torus extend to a distance of $\sim$ 30,000 AU, and has a total (gas + dust) mass of 25 $M_\odot$. The extinction towards the outflow is estimated to be 11 magnitudes of optical extinction and the mid-plane optical depth to L1551 IRS 5 to be 140. This model provides a good fit to the ISO data, as well as the available HST/NICMOS data, and to mid-IR maps, submm radio interferometry, and to ground-based photometry with a range of different aperture sizes.
3. On the basis of the above model, a extinction curve has been estimated, which shows that the emission at wavelengths shorter than $\sim$ 2 μm is due to scattered light from close to L1551 IRS 5, while at wavelengths greater than 4 μm, is seen through the full extinguishing column towards the central source. This need to be taken careful account of when comparing line intensities at different wavelengths.

References

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Men′shchikov, A.B., Henning, Th., Fischer, O. 1999, ApJ, 519, 257 (MHF99)