Introduction

The L1551-IRS 5 source and its associated molecular and atomic outflow have been in focus of front-line research for at least the last 40 years. It was the first object I observed professionally and wrote my first paper on it. Opus No.1 as it were. I found it so interesting that after my thesis about its molecular outflow I have now published more than 20 papers about this object and I am still fascinated by it.

I find it a very important object to study because of its proximity and orientation, and its display of basically all tracers of (low-mass) star formation such as its location at the edge of a dense molecular cloud and its associated Herbig-Haro objects. It has an atomic jet and an aligned molecular outflow that displays well separated blue- and red-shifted outflow lobes. The orientation of the outflow is thus at a shallow angle with respect to the plane of the sky making the resolution of small spatial elements possible. Like the majority of stellar systems, the source IRS 5 is even a binary, each component of which has a solar-system size protostellar disk (Bieging & Cohen, 1985; Rodríguez et al., 1986; Looney et al., 1997; Rodríguez et al., 1998), or maybe even a triple star system (Lim & Takakuwa, 2006). Apparently each of the components has an associated atomic jet (Fridlund & Liseau, 1998), and it has been suggested that there is also individual molecular outflows coming from each component (Wu et al., 2009). This assembly is wrapped inside a larger disk (of roughly Kuiper-Edgeworth belt dimensions) which in itself is found inside a rotating, flattened, molecular gas envelope of Oort cloud dimensions (Fridlund et al., 2002). The two atomic jets emanate from IRS5 A and B and can be traced for some thousands of AU (tens of arc seconds). IRS5 and its associated jet(s) is also one of the first Herbig-Haro type sources where X-ray emission has been discovered (Favata et al., 2002). Herbig Haro jets can thus carry enough energy to create X-ray sources that can be used to further study important physical parameters of low mass jets and their interaction with the ambient medium, and even on short timescales (Favata et al., 2006).

All of this together make the L1551 IRS 5 object a marvellous laboratory in order to study the early phases of star formation and especially how the angular momentum of a collapsing cloudlet is the driving engine for a large number of phenomena accompanying this process. While stellar formation may be understood in principle, much of the details remain unknown, partly because it takes place hidden behind large amounts of extinction, requiring the development of more and more sophisticated techniques in the IR. It would be impossible to cover everything that has been studied and written about this fascinating object here. There are much more than 100 refereed papers written primarily about different aspects of L1551 IRS5 and its associated objects between 1979 and now. Therefore such an endeavour will have to await a proper review article (which appear to be well motivated), and the present article will have to be more of a personal account, sampling certain aspects of L1551 IRS 5.

The molecular cloud L1551

This molecular cloud was noted more than 60 years ago. Herbig obtained the first photographic plates of the region in 1951 (Cudworth & Herbig, 1979), and Sharpless (1959) listed the brightest optical nebulosity visible against the cloud as number 239 (the T-Tauri nebulosity is No 238) in his catalogue of HII regions. The molecular cloud L1551 itself is about 30 arc minutes across (Lynds, 1965), and over the years a number of other important young objects such as L1551 NE, HL & XZ Tau, the HH30 disk and its associated jet, IR sources and eventually several molecular outflows and Herbig-Haro objects have become associated with this cloud. In this article I will restrict myself almost exclusively to L1551 IRS 5 and its associated objects. Under the name of S239, Knapp et al. (1976) carried out very early CO and \(^{13}\)CO observations with the 11m NRAO telescope at Kitt Peak. They found large velocity gradients which they interpreted as the signature of infall of the whole cloud (about 100 \(M_\odot\) of molecular material). These observations led Snell et al. (1980) to make a more detailed study of these molecular tracers, using the 4.9m MWO antenna in Texas, and mapping the kinematics they discovered the first of many bipolar molecular outflows.

Strom et al. (1974) studied HH objects with the objective of acquiring more information about the embedded IR sources that had been discovered during several surveys.
in the late 1960s, and for this purpose they included the HH28, HH29 and HH102 objects. HH102 (ex S239 – see Mundt et al. 1985) turns out to be a reflection nebula, not an HH object (large yellowish nebula to the upper right in Fig.1). Strom et al. (1976) identified a 2.2µm source, that became known as IRS 5. More or less simultaneously, Cudworth & Herbig (1979) had observed two Herbig-Haro objects clearly associated with the L1551 cloud, HH28 and HH29, and, comparing their data with photographic plates obtained in the beginning of the fifties, found that HH28 and HH29 showed significant proper motions. The proper motion vectors also appeared to intersect, when plotted backwards several hundred years in time, at the position of the IRS 5! Finally, again more or less simultaneously, Sandqvist & Bernes (1980) had published observations at 2-mm, 2-cm and 6-cm of H$_2$CO, formaldehyde, that could be modelled as an excellent tracer of density enhancements in molecular clouds, and found a density knot exactly on the position of L1551 IRS 5. This peak in the density indicated that we were dealing with a heavily embedded object , which made it a very nice target for observations in the far infrared (FIR). And Sandqvist & Bernes were in Stockholm....

**Balloon observations from Texas....**

At the end of 1978 I was just finishing my undergraduate studies in Stockholm and was thinking about what to do next when I was approached by Lennart Nordh (then at the Stockholm Observatory) who wanted to know if I was interested in a job. Three weeks later I had moved to Groningen in Holland and was busy acclimatising myself in the FIR balloon group there. Fast forward another five months (May 1979) and I was sitting at the National Center for Atmospheric Research (NCAR) balloon base in Palestine, Texas, carrying out my own first observation of L1551 IRS 5 with a balloon borne 60cm telescope, hanging under a balloon the size of a football field, and operating at 42 km altitude. The photometer had filters transmitting between 72µm and 196µm. From these observations we derived a total flux from IRS 5 of 25 solar luminosities (Fridlund et al., 1980), assuming a distance of 150pc, (L1551 is today considered to be at a distance of
140 pc (Kenyon et al. 1994). So the conclusion was that it was a low mass pre-main-sequence stellar object, associated with the molecular outflow. I remained in Holland until 1981 working on a total of 6 balloon flights observing mainly compact, embedded HII regions. When I returned to Sweden in early 1982 I had a lot of material for my thesis but my advisor (again Lennart Nordh) argued that the launch of the IRAS satellite just around the corner could possibly make my thesis obsolete. He suggested follow-up observations of 1-5\(\mu\)m NIR of my sources, as well as using the 20m mm-telescope at Onsala, Sweden for CO and \(^{13}\)CO observations with much higher spatial resolution than achieved by Snell et al. (1980).

Figure 2: R-band HST image of the HH 154 southern and northern jets in 1996.

Figure 3: HST image of the HH 154 jet in 1996 in the H\(\alpha\). The superimposed contours define the knots within the jet at different epochs: 1996 (blue), 1998 (green), and 2005 (red).

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**Groundbased and satellites**

The NIR observations carried out with the InSb photometer on the ESO 1m telescope in La Silla indicated that IRS 5 had lost more than 1/2 a magnitude in the K-band (2.2\(\mu\)m) with respect to the observations carried out by Strom et al. (1976) which could be indications that a FU Orionis type outburst had taken place recently (Fridlund et al., 1984b; Fridlund, 1987). The CO observations took place under some of the best conditions ever experienced at Onsala and I got beautiful data (Fridlund et al., 1984a). It was obvious to me that this was what my thesis should really be about and I should map the complete outflow at high spatial resolution. As mentioned above, the red- and blue-shifted CO outflow lobes are spatially well separated and have an angular extent of more than 20 arcminutes on the sky. The beam size of the Onsala 20m at the 2.6mm wavelength of CO/\(^{13}\)CO is 30" and I was planning to use a beam spacing of 20" so it was a large project under any conditions, and since the exceptional conditions experienced during my first run never rematerialised it meant that I did not finish the mapping of the blue-shifted outflow lobe until 1986. Those results were published half a year later as my PhD thesis (Fridlund, 1987). The red-shifted outflow lobe was eventually only partially sampled by me. My results demonstrated, nevertheless, clearly that the molecular outflow is mainly composed of the swept-up gas along the surface of the outflow lobe, a result that was confirmed by a more complete study by Moriarty-Scheiven et al. in a series of papers (1987a, 1987b, 1988). The outflow thus has the structure of evacuated edge-enhanced lobes, but it was found around this time that these lobes are filled with neutral atomic (HI) gas participating in the outflow (Lizano et al., 1988). Parenthetically, in January 1983 The Infrared Astronomical Satellite (IRAS) was launched. This was the first-ever space-based observatory and during ten months (until the liquid He cooling the whole spacecraft boiled off) it mapped essentially the whole sky at 12, 25, 60 and 100\(\mu\)m wavelength. Although it produced much better quality data than our balloon telescope, not a single one of our results were changed except providing smaller error bars. IRAS did, however, discover a new embedded FIR source, that became known as L1551 NE about 2.5 arcminutes away from IRS 5 and much weaker – only 9 \(L_\odot\) (Emerson et al., 1984). I remembered something when reading this paper, and looked up the original data from the balloon flight in 1979, and there was L1551 NE, just next to IRS 5 and just barely spatially resolved from it – but with a S/N of only 2.5 (although seen in independent scans in both filters)! So sometimes noise is data (and vice versa) and one has to know which is which.

In the meantime a lot had happened also in the visual wavelength range. Image intensified photographic plates
and the first CCD detectors had become available. With such detectors, optical studies could be carried out in a fraction of the time previously needed when using photographic plates alone. In a large study, the nebulosity very near (< 10 arcseconds) IRS 5 was interpreted as either a jet or an edge-enhanced cavity by Mundt & Fried (1983), who also found that it possessed a very knotted structure. Further studies by Mundt et al. (1985) who obtained spectra of the HH 102 found characteristics of a reflection nebulosity that displayed FU Orionis characteristics (i.e. P Cygni profiles) that they could associate with IRS 5. This was consistent with the 1-5\textmu m observations by Fridlund (1984b, 1987). Sarcander et al., (1985) carried out a spectroscopic investigation of the IRS5 jet (as well as the HH28, HH29 and HH102 nebulosity) and found very high radial velocities in the brightest knot in the jet, as well as being able to estimate the density of the jet for the first time, and calculate that the jet only possessed at most 1% of the required momentum to drive the molecular outflow. Neckel & Staude (1987) then obtained new imaging data and comparing with the old images from Mundt & Fried in 1983, they could detect clear morphological changes in the jet consistent with the velocities > 200 km s\textsuperscript{-1} found in the spectroscopy of Mundt et al (1985) and the proper motions of Sarcander et al. (1985). Stocke et al. (1988) also studied the jet spectroscopically confirming the high radial velocities and also finding strong indications that the visual extinction towards IRS 5 itself could be as high as 150 magnitudes or more. Given the geometry of the outflow, as well as the presence of the HH objects and their velocity vectors, this could immediately be interpreted as having a dense dusty disk orbiting the protostar and being viewed edge on (at right angles to the major axis of the outflow). Observations in the near IR (Campbell et al. (1988)) could also be interpreted in this framework.

Almost all of the Herbig Haro objects are located within the 'blue' CO lobe. The most prominent objects are HH28, HH29 and HH102 are also found within the cavity walls of the 'blue' lobe. Also the IRS 5 jet, which has Herbig Haro characteristics (beginning with Sarcander et al. 1985) and which led to it receiving the designation HH154 in the compilation of Reipurth 1999). Essentially only HH 262 (López et al., 1998) can be found within the 'red' lobe. That more objects are visible in the 'blue' lobe is not so strange since apparently the outflow is emanating out of the cloud here while the 'red' lobe is penetrating into the L1551 cloud itself experiencing a progressively higher extinction. Liseau et al. (2005) found that the outflow is oriented with its major outflow axis most likely at an angle of between 45 and 60 degrees w.r.t. the plane of the sky. The velocity gradients found in CO (Fridlund et al., 1984a), as well as the radial velocity field of both HH29 and that found in the jet (Fridlund & Liseau, 1998; Fridlund et al., 1998), then made it very clear that the outflow that is originating at IRS 5 is interacting with the ambient medium at the position of the HH objects. The proper motion vectors of HH 28 and HH29 had also been found to intersect at IRS 5 when projected backwards in time by Cudworth & Herbig (1979). By observing HH29 (which is unusually bright for an HH object) with the International Ultraviolet Explorer (IUE) satellite, Liseau et al. (1996) found that the individual knots within HH 29 were varying by large factors over times less than 6 weeks (interval between observations). This indicated a very small size scale for the interacting elements, and a time scale for the shocking gas to pass through ambient knots (which must have a density enhancement of at least 10\textsuperscript{4} to produce the UV spectrum), of less than 6 weeks.

It should be noted that Devine et al. (1999, 2000) have found that there appear to be more outflows somewhat criss-crossing each other in the region and those authors argue that some of the HH objects, specifically HH28 and HH29, could be excited by a flow from another YSO (most probably L1551NE). More studies are needed to clarify this. Here we only note that both HH28 and HH29 are spatially within the 'blue' lobe of the outflow originating at IRS 5, as defined by the molecular studies, and this outflow is without doubt the most energetic in the region. The proper motion studies by Cudworth & Herbig (1979) also support this scenario (see below).

Because of the advent of a new detector developed by ESA for the Hubble Space Telescope another opportunity arose. I was now (since 1989) working for ESA and one of my tasks was to take a development of this HST detector and test it on the ground. The detector was a very sensitive photon counting detector, which equipped with very narrow band filters could be used to study the emission lines in nebulae quantitatively. Bringing this instrument to the Nordic Optical telescope in La Palma, Spain, we began by observing HH29 in a number of shock diagnostic emission lines (Fridlund et al., 1993) and continued with observations of the IRS 5 jet, now using a CCD camera instead since they had become more sensitive (Fridlund & Liseau, 1994), where we confirmed and extended the work of Neckel & Staude (1987). The results were so promising it led us to propose a multi-cycle program on the HST with its high spatial resolution. We followed up our observations of HH29 with a program further clarifying the physical parameters such as densities and velocities using the NTT/EMMI echelle spectrograph at ESO, La Silla.

We found densities in the individual knots of HH 29 of 10\textsuperscript{3} cm\textsuperscript{-3} - 10\textsuperscript{4} cm\textsuperscript{-3} within an 'inter-clump' medium with a density of about 300 cm\textsuperscript{-3}, as well as radial velocities of up to 200 km s\textsuperscript{-1}.

The binary of IRS 5 was noted early (Bieging & Cohen, 1985; Rodríguez et al., 1986) in radio observations penetrating the extinction, although it was debated for a few
years whether one was observing a toroid shaped gas disk or the components in a binary. It was interferometric observations that finally could decide that this was a case of two stars being formed within the same envelope (Looney et al., 1997; Rodríguez et al., 1998) and eventually tracing the optical jets disappearing behind the obscuration, each towards one of the two components (Rodríguez et al., 2003a) and finally observing the proper motions of the components and determine their total mass to be 1.2 $M_\odot$ (Rodríguez et al., 2003b). These data were later used by Liseau et al. (2005) to model the physical parameters of the system further, arriving at stellar masses of 0.8 $M_\odot$ and 0.3 $M_\odot$ respectively.

Into deepest space

Our first set of HST WFPC2 observations were carried out in cycles 5 & 6, the results of which can be found in a series of papers. The first results were published in Fridlund & Liseau (1998). We confirmed the binarity of the jet and could connect it to the binarity of IRS 5 itself, as well as identify the two separate velocity systems belonging to the two jets. We further derived the structure of the working surface of the jet (HH154), resolving completely the Mach disk from the bow shock. Comparing with shock models, and having the radial velocities (from observations with the Nordic Optical Telescope) and an estimate for the proper motions of the working surface (from the results quoted above) it was possible to derive the electron density of the jet and we could (again) conclude the jet could not be the driver for the large scale molecular outflow since a) it is lacking at least two orders of magnitude in momentum and b) its dynamic age is 3 orders of magnitude too small thus confirming the results of Sarcander et al (1985). In Fridlund et al. (2005) we presented the complete analysis of the HST data from these cycles.

We found that the highest 'true' velocities within the jet were between 500 and 600 km s$^{-1}$ as well as mapping out the appearance, disappearance and apparent movements of different features within the jet. Specifically we found that the Mach disk of the working surface is moving downstream at a transverse velocity of 180 km s$^{-1}$. In 2002 we observed L1551 with ESA’s X-ray satellite XMM. I was expecting, based on the strong shock characteristics we had found in HH29, that it was most likely that we would find any X-rays there. It was, however, within the jet itself that we discovered an X-ray source (Favata et al., 2002) Later observations (Bally et al., 2003 and Favata et al., 2006) demonstrated that the position of the X-ray source is about 0.8 arc seconds away from IRS 5 itself (about 100 AU), just where the jets emerge from behind the optical extinction. Representative of shock temperatures of 4MK, it appears just where we observe ‘true’ velocities of 500 to 600 s$^{-1}$.

Molecules again

We observed the inner 3 arc minutes by 3 arc minutes around IRS 5 in a number of molecules, HCO+, H$^{13}$CO+, $^{12}$CO and $^{13}$CO, all in the J=1-0 transition, using the Onsala 20m telescope and acquiring very high signal to noise observations (Fridlund et al., 2002). By using all
these isotopomers we could determine the total mass of the gas, its kinematics and the general structure in a region about the size of the Oort cloud in the Solar System. By tracing the self reversal in the HCO$^+$, we believe we have defined the mid plane of the disk. The H$^{13}$CO$^+$, on the other hand is optically thin or near so and have been used to calculate the mass of the disk and its surrounding envelope, which turns out to be about 2.5 $M_\odot$ (excluding the protostars). Kinematically most of this molecular material appears to be rotating, an observation strongly supporting that of Kaifu et al (1984) which was based on observations of CS with the Nobeyama 45m telescope. We also find that the molecular outflow has a very high mass loss rate, $10^{-5}M_\odot$ yr$^{-1}$ confirming the result of Fridlund & Knee (1993).

We also searched for gas phase methanol (CH$_3$OH) and HCN, in the direction of L1551 IRS 5 expecting to see it only directly at the position of the protostar itself, since it should freeze out under the conditions of the disk/envelope. Surprisingly we discovered it essentially all along the rotating flattened envelope (White et al., 2006, see Fig. 5). The only observable heat source that could provide the UV or harder photons is the jet, and modelling the geometry of the situation and knowing the flux of HH154, we found that radiation from the jet could sufficiently heat the surface of the disk tens of thousands of AU away from the jet base.

I would like to finish with some general thoughts about what we see in the area around L1551. Many sets of data covering wavelengths from the X-ray region to cm radio wavelengths are in agreement that some very energetic processes are taking place here at different spatial scales. One may assume that the energy required for these processes is coming from the accretion process, but the gravitational energy released from the collapse of the part of the cloud forming IRS 5 is only part of it. The rotational energy from the large flattened envelope has to be removed as the gas is slowly accreting towards the centre of the forming star system. There is a tremendous amount of angular momentum that need to be transferred into the outflow. The mechanism doing this is still unknown. There may also be a large amount of magnetic energy ‘frozen’ into the rotating gas envelope, and where the diffusion time is significantly longer than the star formation process. The molecular outflow seems to have 2-3 orders of magnitude more momentum than the optically visible atomic jet could deliver to it so it can not – at least not currently – be providing all the input of energy needed into the outflow. There are three components of the outflow that need to be coupled together. The visible jet with velocities of up to more than 500 km s$^{-1}$, the HII flow filling the swept-up cavity with velocities around 150 km s$^{-1}$ and the molecular outflow towards the edges with velocities of around 10-50 km s$^{-1}$. All of these issues, which probably also occur in other star forming regions during the outflow phase, are, in my opinion, elements where the continuing study of L1551 IRS 5 may bring further clarity.

This source has continued to surprise me for a very long time now and I am certain that new observations, especially with ALMA, and the continued monitoring in the optical and X-rays will continue to do so.

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