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THE FORMATION OF A T TAURI STAR:
OBSERVATIONS OF THE INFRARED SOURCE IN L 1551

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5-25 μm observations show that the object discovered by Strom <u>et al</u>. (1976) at 2.2 μm within the densest part of the L1551 dark cloud is a strong source of radiation from grains as cool as 130 K. The energy distribution resembles that of infrared objects embedded within other molecular cloud cores, but implies a total luminosity of only 30 $L_\odot$. The luminosity of the source and its proximity to other T Tauri stars suggests that it is a 1-2 $M_\odot$ pre-main sequence star still swaddled within the L1551 cloud.

The radio and optical evidence for mass motions around IRS 5 (Snell <u>et al</u>. 1980; Cudworth and Herbig 1979) may mean that IRS 5 has been flaring in FU Ori-type eruptions within the last 10^3 years.

Subject Headings: infrared: sources - nebulae:
individual - stars: pre-main-
sequence

I. INTRODUCTION

L1551 is a nearby dark cloud in Taurus (Lynds 1962) which is associated with a number of T Tauri stars and Herbig-Haro objects (figure 1) as well as with CO emission characterized by extremely broad line profiles (Knapp et al. 1976). Strom, Strom and Vrba (1976; hereafter denoted SSV) made 1.2-4.8 μm observations of a number of objects in the vicinity. One source, their #5, hereafter called L1551-IRS 5, showed an energy distribution rising steeply to wavelengths longer than 5 μm, suggesting emission from hot dust surrounding an object embedded within the molecular cloud. The infrared properties of IRS 5 and its location within the dense core of the cloud (Snell 1979; Loren, Evans and Knapp 1980) are similar to those of extremely young, late O or early B stars found within the cores of massive molecular clouds such as S 140, S 255 and Cep A (Beichman, Becklin and Wynn-Williams 1979).

A most intriguing aspect of L1551 is the evidence for large scale mass motions within the molecular cloud apparently centered on the position of IRS 5. Snell, Loren and Plambeck (1980) have found that the broad wings of the CO lines arise in two streams of gas flowing in diametrically opposite directions outward from IRS 5 (figure 1). There is also suggestive optical evidence for the existence of mass motions. A proper motion study of the nearby Herbig-Haro objects HH 28 and HH 29 (Cudworth and Herbig 1979) revealed that these two objects are both moving directly away from IRS 5 at about 150 km s^{-1} in the same direction as the southwest flow of gas seen in CO.

Snell et al. (1980) suggest that the expanding gas and the large proper motions of the HH objects are due to the interaction of a strong stellar wind around IRS 5 with the ambient gas of L1551. The nature of IRS 5 is central to the discussion and in this paper we report 5-25 μm observations of this object.

II. OBSERVATIONS

We observed L1551-IRS 5 on 23 October (UT), 1979 with the newly commissioned NASA Infrared Telescope Facility atop Mauna Kea, Hawaii. The University of Hawaii helium bolometer (Dyck and Simon 1977) was used at the f/35 Cassegrain focus of the 3 meter telescope. The secondary mirror was chopped at 14 Hz with a 30" throw in the north-south direction. Scans across β Peg at 10 and 20 μm showed the focal plane aperture to have a full-width at half-maximum of 3".8. The seeing was about 1" during the course of the night.

Narrow-band filter photometry was calibrated with respect to α Tau whose magnitudes shortward of 18 μm are from Neugebauer (private communication 1979) and longward of 18 μm from Morrison and Simon (1973). The conversion from magnitudes to flux densities is given in Beckwith et al. (1976). The chief sources of photometric uncertainty appear to have been due to guiding and to uncertainties in the calibration. The latter are estimated to be 10 percent shortward of 18 μm and 20 percent longward of 18 μm.

III. DATA

The position of IRS 5 is $\alpha(1950) = 04^h\ 28^m\ 40^s.2$ and $\delta(1950) =$

18° 01' 45" with an uncertainty of ± 2" in each coordinate. The position is derived from incremental encoder readouts of offsets from HL Tau for which an astrometric position is available (Herbig, private communication 1979).

Data taken at positions around the source show it to be smaller than 4" in diameter. There is no evidence for any other source brighter than 1 Jy at 10 μm within 15" of IRS 1.

The photometry of the source is given in Table 1 and Figure 2. The present data overlaps that of SSV only at 4.8 μm with our datum being about a factor of two lower than theirs. The disagreement could be due to the effects of observing a slightly extended source with radically different beam sizes (30" vs. 3".8) or to source variability.

IV. DISCUSSION

Within the accuracy of the radio measurements IRS 5 lies projected against the densest part of the molecular cloud. The observations of Snell (1979) and Loren *et al.* (1980) give a ^{13}CO column density of 7.5×10^{15} cm^{2} and a peak density of 6.3×10^{4} cm^{-3}. The location of IRS 5 is consistent with its having formed as a result of the collapse of the dense core of L1551.

The overall shape of the 1.2-25 μm energy distribution is very similar to those of other sources embedded within molecular clouds such as S140-IRS 1, S255-IRS 1 and IC 1848-IRS 1 (Beichman *et al.* 1979; Blair *et al.* 1978; Evans, Blair, and Beckwith 1977; Loren and Wootten 1978). The spectrum of L1551-IRS 5 rises steeply out to 25 μm and is much broader than that arising from the emission of single temperature dust grains. The 12.8-25 μm color temperature is 130 K ± 5 K for blackbody emission and 112 ± 5 K for grains following a λ^{-1} emissivity law. The 3.4-4.8 μm data of SSV yield a blackbody color temperature of 660 K. Such a broad energy distribution, implying a large range in grain temperature, is consistent with models of the radiative transfer through clouds heated by a central heat source (e.g. Scoville and Kwan 1976).

The ratio of the broadband 10 μm flux to the 10.5 μm narrow-band flux is 1.2 ± 0.1, suggesting the existence of a shallow silicate absorption feature.

Despite its resemblance to infrared sources in other molecular clouds, L1551 - IRS 5 is far less luminous than other embedded objects. At a distance of 140 pc (Elais 1979) the 1.2-25 μm luminosity of IRS 5 is only 2.4 $L_\odot$. The existence of grains as cool as 130 K suggests that much of the emission from IRS 5 comes at wavelengths longer than 25 μm. A comparison with the energy distributions of embedded sources like S 140 and S 255 suggests that as much as ten to twenty times more energy will be emitted at far infrared wavelengths as is emitted shortward of 25 μm. The total luminosity of IRS 5 is probably in the range of 25-50 $L_\odot$. The far infrared observations of Fridlund _et al._ (1980) give a total luminosity of 25 $L_\odot$ in a 4.5 beam.

An independent measure of the total luminosity of IRS 5 comes from assuming that the gas temperature observed in ^{12}CO is the result of collisional heating of the gas by dust grains which are themselves warmed by radiation from IRS 5. The method for calculating far infrared luminosities from CO data described by Evans et al. (1977) can be combined with the ^{12}CO and ^{13}CO observations of Snell (1979) to yield a lower limit of 30 $L_{\odot}$ to the far infrared luminosity of the material within the 12 K contour of Snell's map (within 2'-3' of IRS 5). The energy output required of IRS 5 depends on the fourth power of the assumed dust temperature, T_d, less a correction factor because the grains, even in the absence of IRS 5, have an equilibrium temperature $T_{eq} \simeq$ 10 K due to non-localized heat sources such as cosmic rays (Goldreich and Kwan 1974). For $T_d \gtrsim 15$ K, the correction factor, $1-(T_{eq}/T_d)^4$, is negligible compared with other uncertainties. The assertion that the grains are heated by IRS 5 is supported by equation 9 of Scoville and Kwan (1976) which shows that a 30 $L_{\odot}$ object can heat material 2'-3' away to temperatures of 15-20 K, comparable to the gas temperatures observed at that radial distance from IRS 5.

An energy output of about 30 $L_{\odot}$ is characteristic of a ZAMS A0-A5 star, although the long time scale of evolution of stars of low luminosity and their near vertical approach in the HR diagram to the main sequence makes it dangerous to assign a spectral type on the basis of luminosity alone. Perhaps more meaningful than a comparison with ZAMS stars is one with visible pre-main sequence stars. T Tauri, V 380 Ori and RY Tauri are all emission-line stars associated with dust emission from nearby molecular clouds. Their total luminosities are in the range 10-80 $L_{\odot}$ (Harvey, Thronson and Gatley 1979). IRS 5 may be an object like these stars, or a precursor to them, but still so heavily enshrouded by its parent cloud that no optical star is visible.

It is possible, however, that some of the optical radiation from

IRS 5 is escaping from the cloud. The extended nebula HH 102 (also known as S 239) lies a few arcminutes west of IRS 5. Recent polarimetric measurements (Vrba 1980, private communication) support the suggestion of SSV that HH 102 is a reflection nebula illuminated by light from IRS 5. The spectrum of HH 102 taken by Strom, Grasdalen and Strom (1974) is, then, one of IRS 5 which is responsible for heating the dust observed in the infrared. HH 102, and by inference, IRS 5, show spectral lines characteristic of a low excitation, partially ionized gas.

The spectral lines are quite similar to those seen by Strom _et al_. (1974) in the spectra of the nearby T Tauri stars HL and XZ Tauri, These two stars lie within 0.25 pc of IRS 5 and have luminosities of 10 and 40 $L_{\odot}$, respectively. (Rydgren, Strom and Strom 1976). It seems quite reasonable to assert that IRS 5 is a younger sibling of these stars, born of the same cloud and in the process of becoming a 1-2 $M_{\odot}$ T Tauri star.

Although the majority of visible T Tauri stars studied by Cohen and Kuhi (1979) have luminosities less than 10 $L_{\odot}$, a few have luminosities as high as 80 $L_{\odot}$. The difference between IRS 5 and most T Tauri stars could be due to either its slightly greater mass or earlier evolutionary stage. An alternative explanation for the high luminosity of IRS 5 is the suggestion by Herbig (1977) and Larson (1980) that at any one time about 10 percent of all T Tauri stars will have luminosities in excess of 25 $L_{\odot}$ during the decline in energy output following an FU Ori outburst. During such erruptions, which recur sporadically every 10^3 -10^4 yr, the stellar output increases a hundredfold to 10^3 $L_{\odot}$ and then decays over 10-1000 yr back to less than 10 $L_{\odot}$. The factor of two decrease in the 4.8 μm flux in the approximately five years between the Kitt Peak and

Mauna Kea observations could be due to such a post-outburst decline.

The ejection of matter at high velocities is an almost inescapable part of Larson's model for the FU Ori phenomenon and could account for the kinematics of the streams of gas seen in CO for the large motions of the HH objects. In this view the HH objects are the interstellar bullets envisioned by Dopita (1978) and by Norman and Silk (1979), accelerated by IRS 5 during periods of high luminosity.

V. CONCLUSIONS

The object found by SSV at 2.2 μm shows an energy distribution out to 25 μm characteristic of hot dust with temperatures between 130 and 600 K. The luminosity shortward of 25 μm is 2.4 $L_\odot$ and an extrapolation to longer wavelengths implies a total luminosity of about 30 $L_\odot$, consistent with far-infrared results. A star as late as A0-A5 and perhaps similar to the T Tauri stars found nearby has formed, or is forming, in the same manner as more massive OB stars--namely as the result of the collapse of a dense, 10^5 cm^{-3}, molecular cloud core.

Accounting for the present high luminosity of IRS 5 and the mass motions in its vicinity may require that IRS 5 have experienced a number of FU Ori-type outbursts within the last 2000 yr.

TABLE 1

Infrared Fluxes from L1551 - IRS 5

$\lambda(\mu m)$		$S_\nu(Jy)$
4.8		0.50 ± 0.07
10.5		2.3 ± 0.1
10	(broadband)	2.8 ± 0.2
12.8		6.9 ± 0.6
18		20 ± 2
20	(broadband)	37 ± 2
25		63 ± 6

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FIGURE CAPTIONS

Figure 1. A schematic drawing of the region around L1551-IRS 5 with north up and east to the left. IRS 5 is denoted by a large filled circle. The Herbig-Haro objects HH 28 and 29 and the Tauri stars HL Tau and XZ Tau are shown as small filled circles. The extended nebula HH 102 is denoted by the hatched area west of IRS 5.

The lines joining IRS 5, HH 28 and HH 29 approximate the direction of motions inferred from the proper motions observed by Cudworth and Herbig (1979). As these authors point out, if the proper motions are interpreted as real space velocities, then HH 28 and HH 29 were in the vicinity of IRS 5, 2000 and 600 years ago, respectively.

The dashed contours show the extent of the CO streams observed by Snell _et al_. (1980). HH 28, HH 29 and the southwest stream of gas are all moving radially toward the observer (Snell _et al_. , 1980; Strom _et al_., 1974).

Figure 2. The photometry from Mauna Kea circles is combined with that from SSV (triangles). One sigma errors are shown on the Mauna Kea data if these exceed the size of the filled circles.

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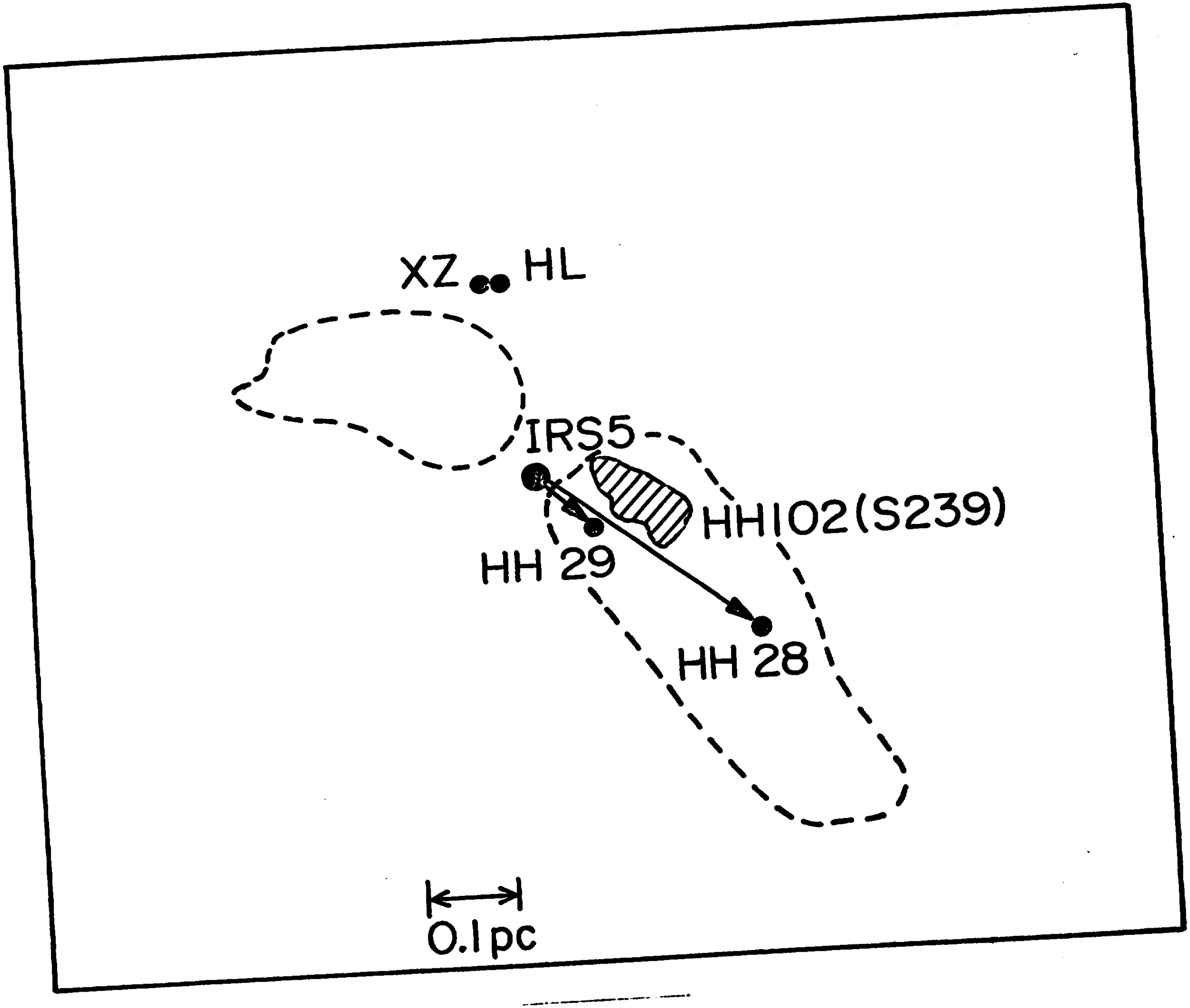


Figure 1

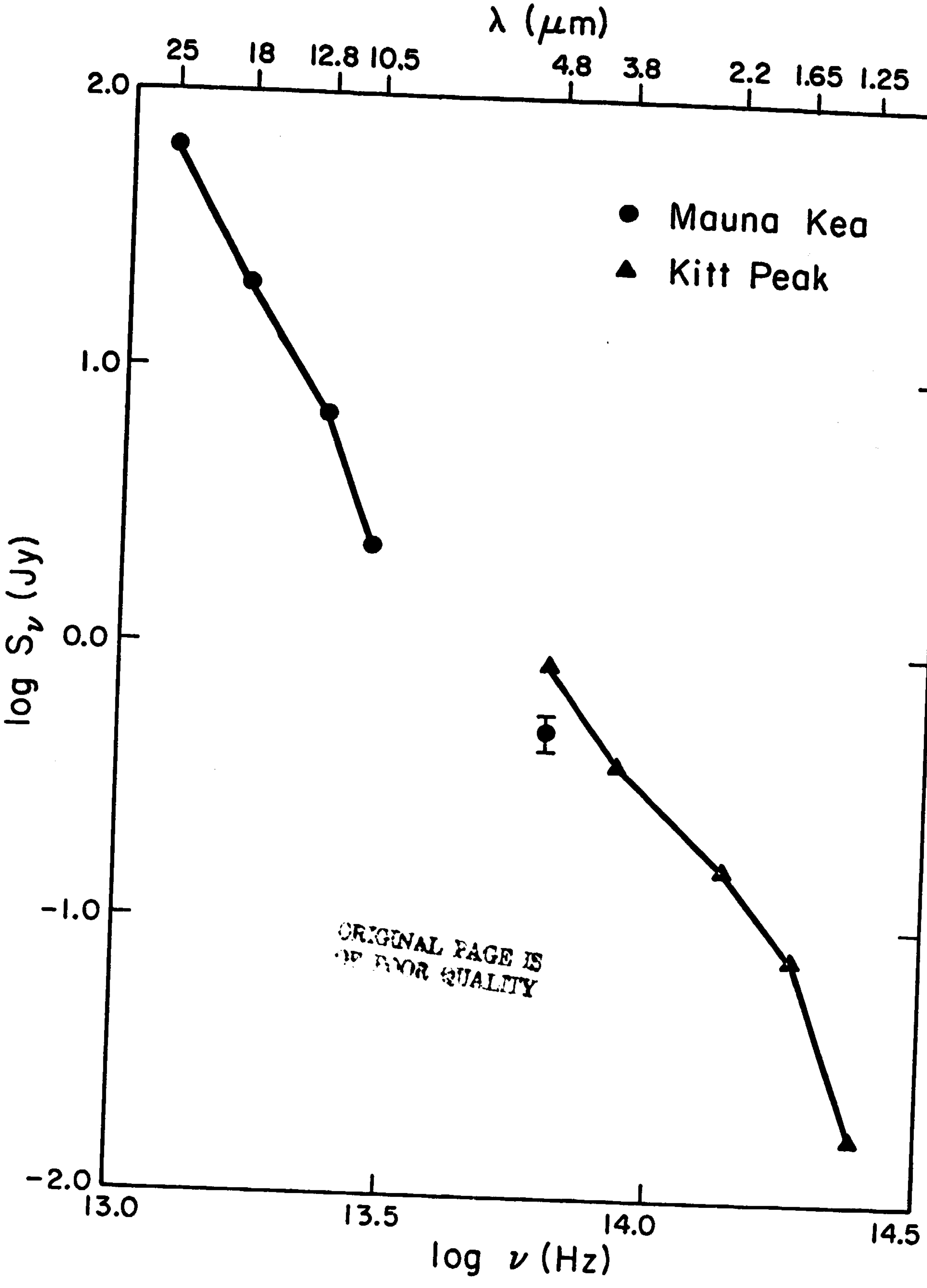

λ (μm)
25
18
12.8
10.5
4.8
3.8
2.2
1.65
1.25
2.0
1.0
0.0
−1.0
−2.0
log S_ν (Jy)
● Mauna Kea
▲ Kitt Peak
13.0
13.5
14.0
14.5
log ν (Hz)

Figure 2

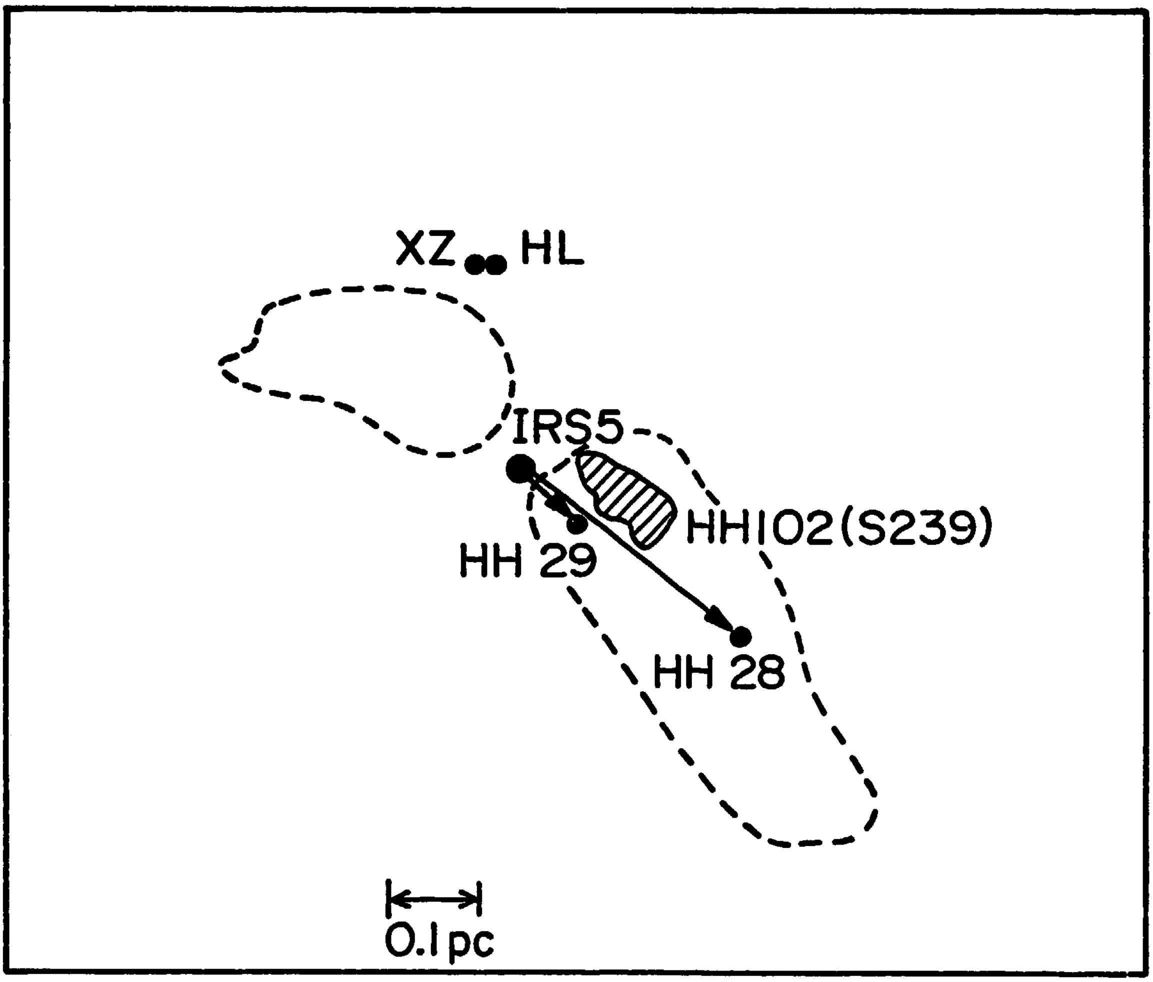
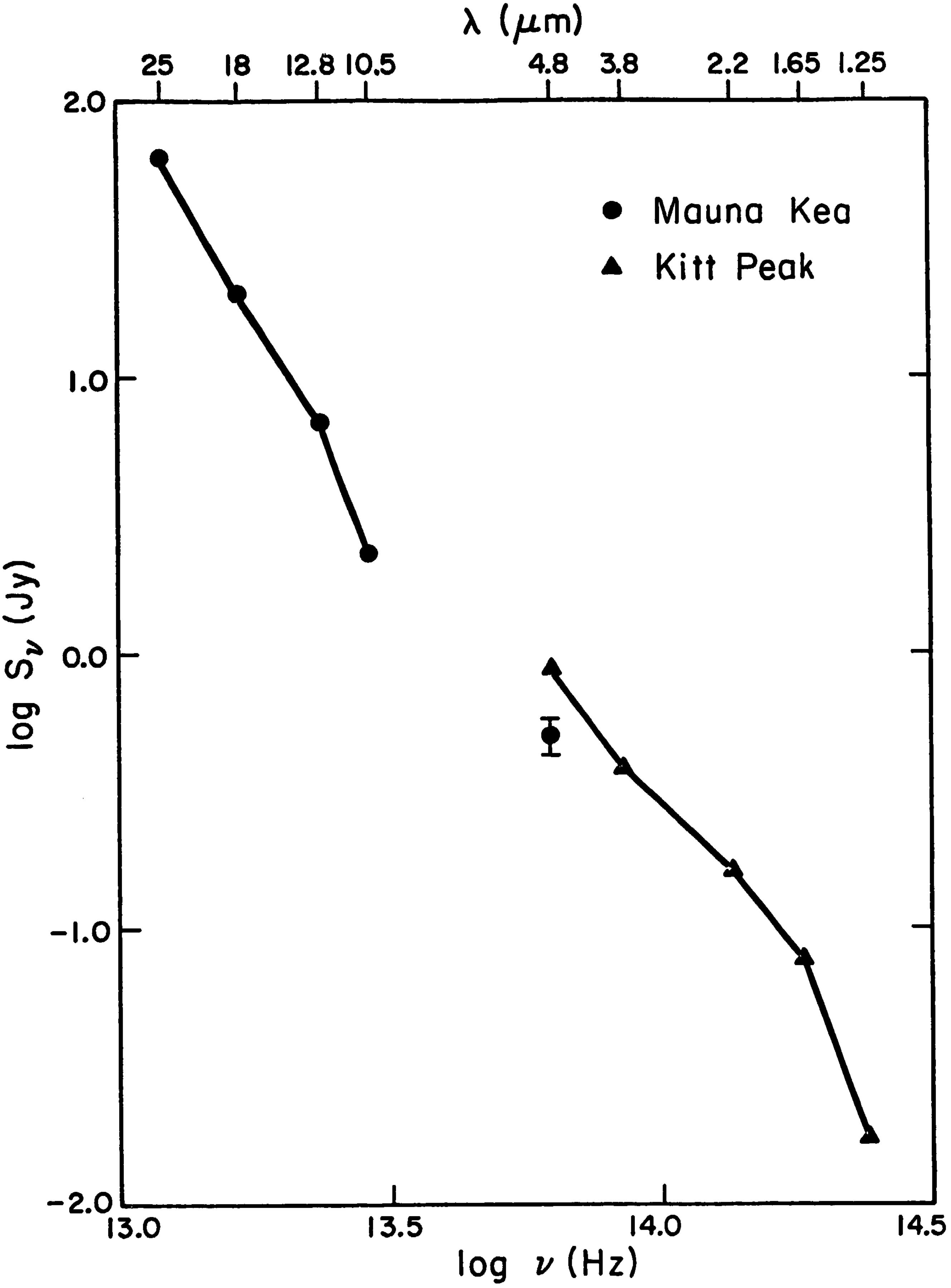


Figure 1


λ (μm)
25
18
12.8
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4.8
3.8
2.2
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1.0
0.0
-1.0
-2.0
log S$_\nu$ (Jy)
● Mauna Kea
▲ Kitt Peak
13.0
13.5
14.0
14.5
log ν (Hz)

Figure 2