

## Near Infrared Spectroscopy of W 51 IRS-2

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**Summary.** Near-infrared spectra at 2.95–3.5  $\mu\text{m}$  and 3.99–10  $\mu\text{m}$  have been obtained towards W 51 IRS-2 and its surroundings, in order to investigate the spatial variations in intensity of the 3.28  $\mu\text{m}$  unidentified feature and the 4.05  $\mu\text{m}$  Brackett- $\alpha$  line. The Br $\alpha$  and 3.28  $\mu$  features occupy a broadly similar spatial zone, which is characterised by an unresolved core responsible for most of the emission, and an extended and considerably weaker halo. Grain properties required to excite the 3.28  $\mu\text{m}$  line, the nature of the 3.28  $\mu\text{m}$  emission, and its relation to the source structure are discussed.

**Key words:** W 51 – infrared spectroscopy

### Introduction

The radio complex W 51 is one of the most massive and extended regions of star formation in the Galaxy. At least three major molecular complexes are seen in projection against a confined area of sky, in consequence of which extinction levels are high (cf. Harris and Lemke, 1981) and the kinematic structure of H I and H II zones is complex (Mufson and Liszt, 1979; Goudis and Hippelein, 1982).

Thermal radio sources delineate the main zones of star formation (Martin, 1972), with G 49.5–0.4  $g$  and  $f$  representing possible blisters at the edge of a molecular cloud. The more compact source W 51d is associated with the near-infrared object IRS 2, whose peak is displaced by  $\sim 4''$  from the core of the H II region.

The continuum spectrum of this infrared source peaks at  $\lambda \sim 70 \mu\text{m}$ , suggesting a massive dust thermosphere with an effective temperature  $\sim 68 \text{ K}$  (Erickson and Tokunaga, 1980). This is supported by other evidence, including an estimated extinction of  $A_v > 32 \text{ mag}$  from S III observations at 0.95  $\mu\text{m}$  (Goudis and Hippelein, 1982), near-IR line/continuum extinction measurements (Puetter et al., 1979; Soifer et al., 1976; Wynn-Williams et al., 1974; Harris and Lemke, 1981), and deep silicate absorption (Genzel et al., 1982). These features, combined with a high source luminosity ( $L \sim 2.8 \cdot 10^6 L_\odot$ ; Erickson and Tokunaga, 1980), broad millimetre wave molecular linewidths (Downes et al., 1982) and evidence for shocked H<sub>2</sub> quadrupole emission (Beckwith and Zuckerman, 1982), make W 51 IRS-2 an extremely interesting region of star formation.

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In this paper we present near infrared spectra at 2.95–3.50  $\mu\text{m}$  and 3.99–4.10  $\mu\text{m}$ , as well as measurements of the spatial distribution of the Brackett- $\alpha$  line and the 3.28  $\mu\text{m}$  unidentified emission feature.

### The Observations

W 51 IRS-2 was observed in June 1981 with the 3.8 m United Kingdom Infrared Telescope (UKIRT) at Mauna Kea, Hawaii. A filter spectrometer with  $\lambda/\Delta\lambda$  of 100 was operated at the  $f/35$  Cassegrain focus. The beam size was  $7''.5$  and the E–W chop throw was  $52''$ . Pointing was determined by off-setting from the 2.2  $\mu\text{m}$  peak of the source and was good to  $\sim 1''$ . Calibration and removal of atmospheric lines was derived from observations of standard stars at similar elevations.

### Discussion

The near infrared spectrum of W 51 IRS-2 (Fig. 1) is seen to exhibit a steep dust emission continuum, recombination lines due to Pfund- $\epsilon$  (3.04  $\mu\text{m}$ ) and Brackett- $\alpha$  (4.05  $\mu\text{m}$ ), and the 3.28  $\mu\text{m}$  unidentified emission feature. We were able to position IRS-2 in our beam whilst not including the nearby compact H II region (Genzel et al., 1982).

In order to examine the spatial variation of the Brackett- $\alpha$  and 3.28  $\mu\text{m}$  features, spectra were obtained in a strip at beamwidth intervals north of IRS-2. These data are shown in Fig. 2, together with the distribution of continuum emission observed in broad band filters at 4, 5, 10, and 20  $\mu\text{m}$ .

Within  $9''$  of IRS-2, the 3.28  $\mu\text{m}$  feature is seen to be more extended than the 20  $\mu\text{m}$  emission and Brackett- $\alpha$ . At distances greater than  $9''$ , both the 3.28  $\mu\text{m}$  feature and the Brackett- $\alpha$  lines are enhanced, indicating an extended distribution of ionized material out to  $\sim 16''$  from IRS-2, after which both lines decrease in intensity.

The extended Brackett- $\alpha$  emission probably arises in an H II blister around the ionizing source. We may derive the emission  $E$  of this region through

$$F(\text{Br}\alpha) \sim 3.2 \cdot 10^{-17} \left\{ \frac{j(5-4)}{j(5-2)} \right\} \left\{ \frac{j(5-2)}{j(4-2)} \right\} \cdot (E/\text{cm}^{-6} \text{ pc}) \text{ erg cm}^{-2} \text{ s}^{-1} \quad (1)$$

whence

$$E = 4.0 \cdot 10^{17} (F(\text{Br}\alpha)/\text{erg cm}^{-2} \text{ s}^{-1}) \text{ cm}^{-6} \text{ pc}$$

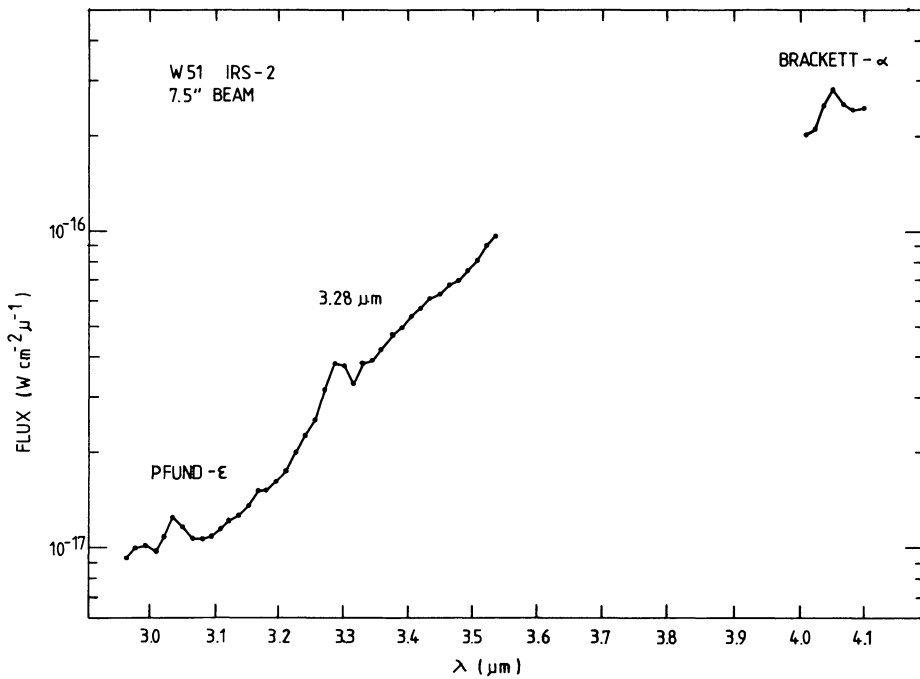


Fig. 1. Spectrum of W 51 IRS-2 obtained with a 7" beam diameter and resolving power of 100

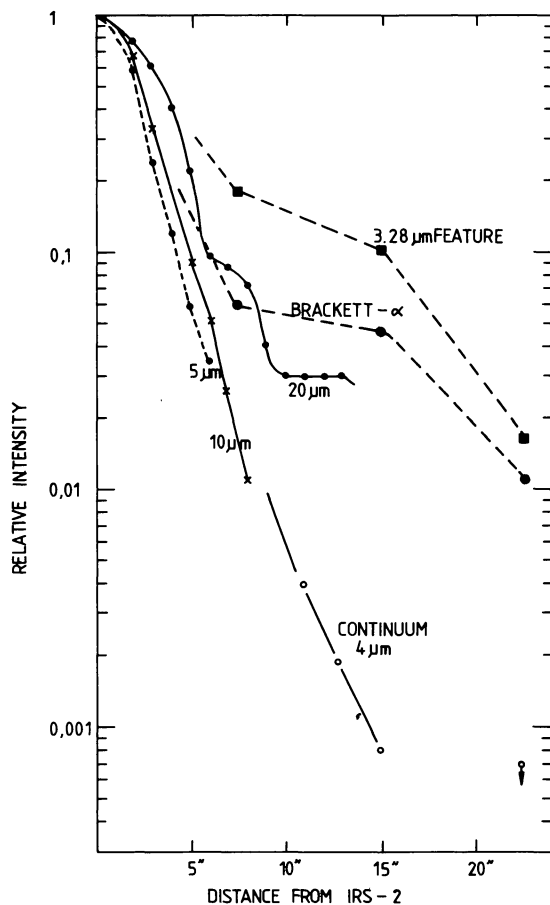


Fig. 2. Peak intensity variations of the 3.28  $\mu\text{m}$  and Brackett- $\alpha$  lines with distance northwards from IRS-2. We have adopted the continuum profiles at  $\lambda \sim 4 \mu\text{m}$  from the present data (7" beam) and at 5, 10, and 20  $\mu\text{m}$  from Hackwell et al. (1982, 3" beam)

based on an effective recombination coefficient  $\alpha_{H\beta}$  from Brockelhurst (1971) appropriate for case B conditions,  $T \sim 10^4$  K, and  $n_e \sim 10^2 - 10^4 \text{ cm}^{-3}$ .  $F$  is the observed flux,  $j(5-4)$  is the emission coefficient of Br $\alpha$ , and we have assumed the halo to completely fill our 7" beam. We find an emission measure  $E \sim 2.2 \cdot 10^6 \text{ cm}^{-6} \text{ pc}$  at radii  $\sim 0.5 \text{ pc}$  from IRS-2. For a line of sight of 1 pc through the H II region, the electron density would then be  $n_e \sim 1.5 \cdot 10^3 \text{ cm}^{-3}$ .

The 3.28  $\mu\text{m}$  distribution is similar to that of Brackett- $\alpha$ , although less centrally peaked. At the source centre we estimate Pfund- $\delta$  to contribute  $\sim 25\%$  of the observed intensity at 3.28  $\mu\text{m}$ , and a lower proportion away from IRS-2 [where we assume  $F(\text{P}\delta)/F(\text{Br}\alpha) \sim \text{const}$ ]. Correction for this additional flux results in a slight flattening of the 3.28  $\mu\text{m}$  distribution at radii  $\leq 15''$ . High-resolution maps of this line in other sources show that the 3.28  $\mu\text{m}$  zone is often adjacent to, but outside the H II region, as in the case of Orion (Sellgren, 1981). The present results suggest however that the 3.28  $\mu\text{m}$  emitters are co-spatial with the H II region around IRS-2. Certainly the distribution of 3.28  $\mu\text{m}$  emission, peaking as it does at the central IR source, differs radically from that of Orion.

An alternative model, suggested for GL 437 by Wynn-Williams et al. (1981), would be to regard the apparent agreement of H II region and 3.28  $\mu\text{m}$  emission in W 51 IRS-2 as a line of sight effect, the H II region being viewed either against or behind the 3.28  $\mu\text{m}$  region. In this case the apparent absence of an annular enhancement suggests that the 3.28  $\mu\text{m}$  emission does not wrap around the blister, although our low resolution may miss such an effect.

How does the distribution of 3.28  $\mu\text{m}$  emission fit into our current ideas of the origin of this feature? In the fluorescence mechanism of Allamandola et al. (1979) 3.28  $\mu\text{m}$  emission is taken to arise from the UV excitation, and subsequent decay of vibrational states in cool grains. Alternatively Dweck et al. (1980) postulate a low number of small ( $\sim 0.01 \mu\text{m}$ ), hot ( $T_{\text{gr}} \sim 300 \text{ K}$ ) grains, which excite oscillators within a thin grain mantle, perhaps

of polymerised ices. In the latter hypothesis, for a grain with emission coefficient

$$\bar{Q}(a, T_{\text{gr}}) \sim CT_{\text{gr}}^2 a \quad (2)$$

at infrared wavelengths (Gilman, 1974), and  $\bar{Q} \sim 1$  in the ultraviolet, an upper limit to the grain temperature outside the H II zone would be

$$T_{\text{gr}} \sim \left| \frac{\alpha L_*}{16\pi C \sigma a} \right|^{1/6} R^{-1/3}, \quad (3)$$

where  $R$  is the distance from the source,  $\sigma$  the Stefan-Boltzmann constant,  $a$  the grain radius,  $C$  is a constant, and  $\alpha L_*$  is the total non-ionising flux. If  $a \sim 0.1 \mu\text{m}$  for the main mass component of the grains, then for  $R \sim 0.5 \text{ pc}$ ,  $C \sim 1.3 \cdot 10^{-2}$  (appropriate for graphite), and  $\alpha \sim 0.5$ , we obtain  $T_{\text{gr}} \sim 135 \text{ K}$ . For the small grains considered by Dwek et al. (1980) with  $a \sim 0.01 \mu\text{m}$ , we find  $T_{\text{gr}} \sim 200 \text{ K}$ . If the small grain component were not directly irradiated by the source, but shielded behind grains with  $a \sim 0.1 \mu\text{m}$ , the radiation field (and the temperature of the smaller grains) would probably be cooler than the maximum value for  $a \sim 0.1 \mu\text{m}$  determined above (cf. Scoville and Kwan, 1976), typically  $T_{\text{gr}} \sim 100 \text{ K}$  at  $R \sim 0.5 \text{ pc}$ . If the  $3.28 \mu\text{m}$  emitters are outside the H II region, therefore, the  $0.01 \mu\text{m}$  grains can have a high temperature only if they are within  $\sim 1$  extinction optical depth of the H II/H I interface.

For comparison, the observed brightness temperature of the  $3.28 \mu\text{m}$  feature is  $T_B \sim 188 \text{ K}$ ; and, whilst grain temperatures  $T_{\text{gr}}$  could be higher depending on emissivity  $\epsilon$ , the ratio  $T_{\text{gr}}/T_B$  is insensitive to  $\epsilon$ , and  $T_{\text{gr}}$  and  $T_B$  are unlikely to differ greatly. The present observations therefore seem to be broadly explainable by the model of Dwek et al., provided that the  $3.28 \mu\text{m}$  oscillators are excited at temperatures as low as  $\sim 200 \text{ K}$ , or that grain sizes are smaller than  $a \sim 0.01 \mu\text{m}$  at  $R \sim 0.5 \text{ pc}$ , and the  $3.28 \mu\text{m}$  emissivity is small.

## Conclusions

Infrared spectra have been obtained from the area around W 51 IRS-2 showing emission lines of Pfund- $\delta$ , Brackett- $\alpha$  and the  $3.28 \mu\text{m}$  unidentified feature. Measurements of the distribution of

$3.28 \mu\text{m}$  and Brackett- $\alpha$  emission show a bright core zone, surrounded by a weaker halo region. These results may be explained if the  $3.28 \mu\text{m}$  emission is projected against a H II blister. The brightness temperature of the  $3.28 \mu\text{m}$  feature,  $T_B \sim 188 \text{ K}$  at  $R \sim 15''$ , is similar to the temperature expected for grains of radius  $\sim 0.01 \mu\text{m}$ , irradiated by the central source.

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