STAR FORMATION AS SEEN BY THE INFRARED ARRAY CAMERA ON *SPITZER*

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ABSTRACT

The Infrared Array Camera (IRAC) onboard *Spitzer* has imaged regions of star formation (SF) in its four IR bands with spatial resolutions of ~2"/ pixel. IRAC is sensitive enough to detect very faint, embedded young stars at levels of tens of Jy, and IRAC photometry can categorize their stages of development: from young protostars with infalling envelopes (Class 0/I) to stars whose infrared excesses derive from accreting circumstellar disks (Class II) to evolved stars dominated by photospheric emission. The IRAC images also clearly reveal and help diagnose associated regions of shocked and/or PDR emission in the clouds; we find existing models provide a good start at explaining the continuum of the SF regions IRAC observes.

1. LOW MASS STAR FORMATION

IRAC [1] has the ability to address directly at least three of the key outstanding observational issues in SF: it can sample thoroughly the low-mass end of the IMF thanks to its great sensitivity (down to a few microJy – about 21^m at 3.6 m and 16^m at 8.0 m), and so can provide astronomers with an accurate census; it can obtain four-color photometry of the mid-IR SEDs of young stars in the spectral region where extinction effects start to become minimal; and it can image large fields-of-view to provide simultaneous information about the circumstellar and interstellar environments in which young stars form. During its first year of operations IRAC's four-band images of molecular clouds have yielded extensive color-color plots of the embedded point sources and the ISM – plots that have already provided a powerful new diagnostic tool for exploring the properties of the protostars developing in these regions. In this short paper we will attempt to give an overview on all three contributions, with a more detailed discussion of the high mass SF ongoing in DR21.

1.1 Point Sources in Young Stellar Clusters

Lori Allen and her colleagues [2] have extended the SED models of YSOs, disks, and accretion processes to the IRAC bands, including in their models the effects of an inner disk wall illuminated by the central star. Their computed SEDs show that IRAC color-color plots may in many cases help to break the ambiguity in YSO class estimates that exist in traditional [J-H] vs [H-K] diagrams. Fig.1 labels the regions of the plot by Class as determined from the models and extinction. Allen finds as much as two magnitudes of color spread across each set of IRAC band colors in the low mass YSO diagnostic diagram. As part of the IRAC team's survey of young stellar clusters, Megeath *et al.* [3] analyzed the point sources in four young stellar clusters in clouds of comparable masses (roughly about 1000 M of gas in each): Cep C, S171, S140, and NGC7129. The color-

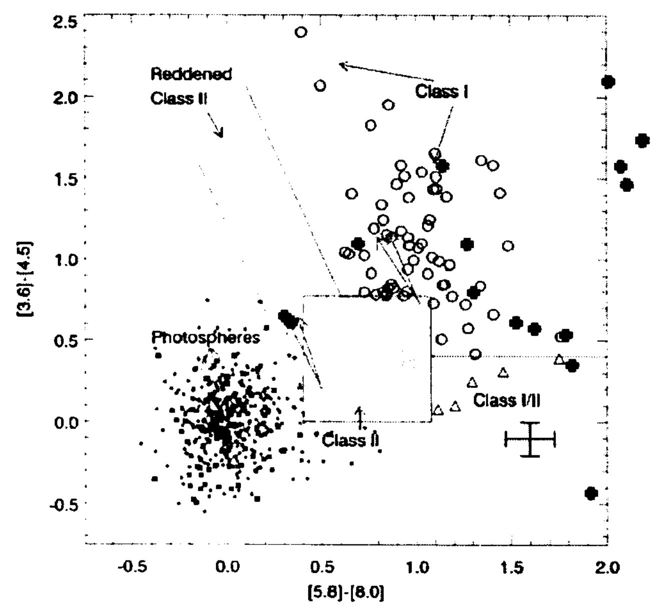

Fig. 1. An IRAC color-color plot of YSOs.

color diagram of sources for these clusters seen in Fig.1 fills the model space more-or-less as predicted with over 200 observed YSOs. Fig. 1 also includes sources from the DR21 complex marked as filled pluses.

2. HIGH MASS STAR FORMATION

2.1 The DR21 Complex

IRAC has obtained four-color images [4] of the nebulosity and point source distribution throughout the giant cloud extending across about one degree – from the ridge of massive SF in W75 in the north past the DR21 complex of massive stars in the south, and including the DB16 cluster in the southwest. It has been suggested [5] there is evidence for an evolutionary trend in activity across this ridge, perhaps either triggered by a cloud-cloud collision [6] or a SNR [7]; the issue is still unresolved. Fig. 2 shows a portion of the IRAC image around DR21.

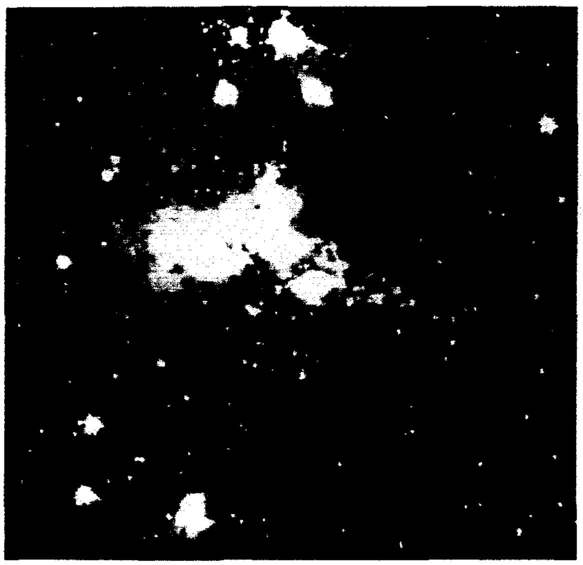

Fig. 2. The DR21 main complex as imaged by IRAC.

The DR21 cloud region is noted for having one of the most massive outflows in the galaxy with velocities of 60km/s or more and an outflow mass estimated at 3000Mo. The force driving this flow, estimated from the shocked H_2 emission to be $5x10^{30}$ dynes, is larger than that in the Orion outflow [8]. The energy is in excess of $2x10^{48}$ ergs, and the luminosity of the H_2 flow alone is 1800 L . Davis and Smith [9] conclude there are both J and C-type shocks at work in the region; others [10] claim evidence for a second "highly collimated" flow perpendicular to the main one. The IRAS satellite detected a very bright source (IRAS 20372+4209, later dubbed IRS1) near the presumptive origin of the massive CO/shocked H_2 outflow, with flux densities of 62.5, 1400, $2.60x10^4$, and $2.22x10^4$ Jy, respectively, in the four IRAS bands. The catalog position is 20h37m16.2s and 42d09m09s (B1950). (The radio source W75S = DR21OH is located about 3' north of IRS1; IRAC finds a weak 3.5 m source at this radio location.)

2.2 IRAC Photometry of DR21 Sources

IRAC has resolved hundreds of faint, red or extremely red stars in the nebulosity associated with DR21, with the dominant cluster of massive young stars lying buried in the bright western lobe near IRS1. Fifteen distinct stars are seen in this lobe by IRAC; we find several more visible in deep H-band images taken with the MMT 6.5m infrared camera. Fig. 3 plots the SEDs of these sources

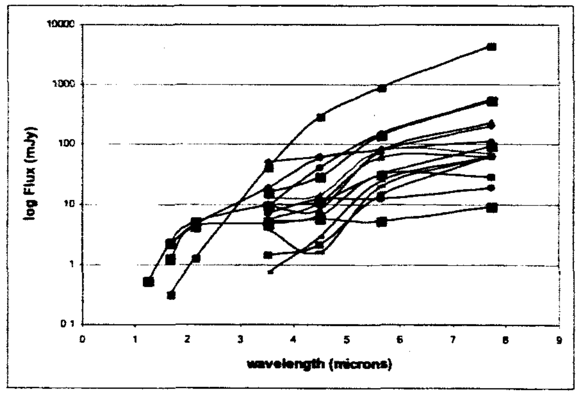

Fig. 3. SEDs of the sources in the main DR21 cloud.

from [J] (when available) through [IRAC B4]. Most sources have very steeply rising spectra, with the most extreme source being one labeled "IRAC-4." While there are 15 sources apparent in Band 1 (3.6 m), in Band 4 (8 m) there is only bright source: IRAC-4, whose flux density is ~2.5 Jy (it saturated the IRAC pixels). Models of YSO SEDs are able to use the spectral index α of the continuum as a measure of the stage of evolution [11]; α>0.3 is indicative of a Class I protostar. The SED of IRAC-4, whose α 5.0, suggests an even earlier stage of development like Class 0. Fig.1 includes the DR21 YSO colors; some are so red the points fall outside the box.

2.3 The Misidentification of IRS1

IRAC, with its relatively good spatial resolution, can play a critical role in identifying unambiguously the key point sources in SF regions. Although the IRAS source IRS1 is extremely bright, the IRAS coordinates are not precise (the IRAS PSC does not include it, but it is in the IRAS Serendipitous Survey which has greater depth and sensitivity in confused areas like DR21). The position does not correspond with any other known source: it lies 6.2" ENE of a [K]= 14.5mag 2MASS source, 2MASS 20390353+4219420, and about 55"WNW of the radio source DR21(CO). 6cm continuum observations [12] found four compact HII regions in this region with the northern-most source, "D", at 20h39m01.25s +42d19'53.4"(J2000), attributed to an O8 ZAMS star. Recent VLA observations in the recombination lines [10] attribute the radio emission to a dual cometary HII region, with source "D" being responsible for one of them. A near-IR study of compact HII regions [13] concludes the main radio sources in DR21 have no NIR counterpart and therefore may have little to do with the SF in the region. In the FIR, Colome [14] mapped the source from the KAO at 50 m and 100 m and report flux densities of 1.58x10^{4}Jy and 3.86x10^{4}Jy, respectively, consistent with IRAS values, but their absolute positions are considerably less certain than the IRAS ones [15].

The first reference to IRS1 and its position is in [16] which cites the position (K-band) as 20h37m13.4s +42d08m59s. (Earlier papers do not mention IRS1: [12] for example imaged the region in the IR and Br but did not note that source "D" is 11" away). But, according to [17]) the identification of IRS1 in [16] was simply made on the basis of it being the brightest 2 m source in the region. [9] and [18] locate IRS1 on their shocked H_2 images, but the position is based on [16] – none of these authors demonstrate that the source they label IRS1 is actually the IRAS source with 63Jy of flux at 12 m. If this IRAS flux is approximately correct we would expect to see it very clearly in IRAC Band 4; we don't. Furthermore, we find the source located at the position of the [16] "IRS1 star" has flux densities of 19.2mJy, 58.5mJy, 81.4mJy, and 115mJy in the four IRAC bands respectively (the Band 4 flux is confused by strong diffuse emission). We conclude that IRS1 has been misidentified in previous visible and near infrared studies, and that by far the most luminous star, presumably a key player in the dynamics, is a faint field star that was previously unnoticed: IRAC-4.

2.4 The Luminous Source IRAC-4

IRAC-4, at 20h39m01.21s +42d19'54.0"(J2000), lies about 23" WNW of the nominal IRAS "IRS1" location. There is no 2MASS source found at this location near the edge of the most heavily obscured portion of the dark lane, but our MMT 6.5-m [H] images see it clearly. If the IRAS flux densities are correct and only the position is uncertain (consistent with the KAO 50 m photometry of the source [14]), then at a distance of about 3 kpc the total luminosity is equivalent to that from an O8 ZAMS star as previously suggested [12]. For an O8 ZAMS star to have these observed infrared fluxes, and in particular to be over1000 times fainter at 2.2 m than at 8 m, the extinction to the source must be approximately Av~175m, a number in rough agreement with estimates of the general region from Br and radio continuum observations [12].

The 14 other sources IRAC finds in the bright western lobe, at the base of the outflow, include some which are also associated with compact HII regions and probably also are O stars. Fig. 1 contains points for these sources, most of which fall outside the region associated with Class II accretion-disks but are well within the region encompassed by envelope models.

3. THE MASSIVE PROTOSTAR IN DR21

We argue that IRAC-4 = IRS1 is a high mass YSO -- a star that is old enough to have developed a compact HII region and powerful wind, but which is still surrounded by a hot, infalling envelope. High mass YSOs are observationally rare in part because they evolve quickly, are hard to identify due to the obscuration that still surrounds them, and because they form in complex clusters. Partly as a result they are less well understood than their low-mass (T-Tauri-like) counterparts. IRAC-4 is coincident with the radio continuum source "D." An O8 ZAMS star has a luminosity of 6.5x10^{4}Lo, but the FIR luminosity of the source [14] is about one order of magnitude larger, 5x10^{5}Lo (assuming d=3kpc). Some correction must be made for the contribution of the rest of the cluster to the IRAS and KAO fluxes, but it appears that the majority of the luminosity of IRAC-4 does not come from the stellar photosphere; we suggest it comes from accretion.

Osorio *et al.* [19] note that most young embedded massive stars have large accretion rates (>4x10^{-4}Mo/yr) that power a luminosity that exceeds the stars' photospheres, but add that most have not yet had time to develop a compact HII region; they find ~1.5x10^{5}Lo can be produced from a hot core with an infall. IRAC-4, therefore, which does appear to host a compact HII region, is presumably in the process of moving from the "hot molecular core" phase onto the main-sequence but is still surrounded by a dust envelope (and/or perhaps a disk; [2; 20]), putting its age at much less than ~1MY and perhaps even less than 10^5 years. The SED of IRAC-4 rises steeply, in agreement with other candidate high mass YSOs [21,22] although some of its SED arises in part because of the extinction at K-band; it rises at longer wavelengths because of this warm dust from the accreting envelope [20]. IRAC-4 may not be only contributor to the outflow however. From our data we cannot determine how many of the 15 core stars have outflows, or whether the massive DR21 outflow is the result of multiple outflows, but multiple, non-aligned flows might be present: [10] argues that the HII region source "D" associated with IRAC-4 has a cometary morphology and that, together with radio source "A" (our source IRAC-10) it forms a dual, nearly perpendicular cometary flow. Smith and Fischer [23] first suggested that there were probably multiple outflows in such regions. One of the complexities in modeling high mass star formation is the powerful radiation which tends to inhibit the envelope accretion. The IRAC-4 source, which is coincident with an HII region at 6 cm, appears to be a rare example of a massive young star which has evolved to produce a compact HII region, but which is still surrounded by an accreting dust envelope -- the outflow thereby provides strong evidence that the current accretion is not symmetric.

4. THE MASSIVE OUTFLOW IN DR21

The IRAC maps distinctly reveal the massive outflow in DR21, as well as image the diffuse, extended PDR regions nearby. Comparison between the IRAC outflow images and 2 m shocked H_2 images shows a very close structural correspondence. Strong lines of v=1-0 CO, Brα, and PAHs features fall in the IRAC bandpasses, and these species have been proposed as being dominant contributors to the band fluxes. However there are over 70 detectable H_2 lines that also fall in the IRAC range, most of which have never before been observed. We have estimated their contribution to the IRAC images of DR21 using a range of PDR parameters [24] and C-shock parameters [25]. Fig.4 plots (as filled circles) the colors expected from H_2 line emission across a range of likely conditions for PDRs and shocks; it also plots the emission expected from diffuse PDR illuminated grains [26]. The figure also plots the range of observed ISM colors (dotted area). The outflow region's points mostly fall across the upper and central range of the dotted zone, while the diffuse ISM points (far from the outflow) have colors at

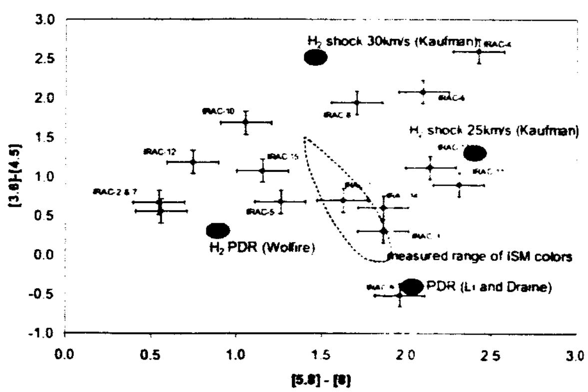

Fig. 4. Colors of the DR21 ISM, with point sources. The dotted range spans the observed ISM colors in both the outflow and the diffuse ISM; filled circles are representative theoretical predictions.

the lower right of the dotted range. Our preliminary results confirm what had previously been suspected - that the outflow is not the result of a simple, single C-shock but rather is a blend of several sets of conditions. The ISO satellite measured the H_2 0-0 S(5) 6.91 m flux in DR21 [18]. The value implies that (depending somewhat on the details of the C-shock) the H_2 lines as a group are the dominant contributors (~30% - 60%) to the total flux observed in IRAC Bands 2 and 3. This conclusion helps to explain the close similarities between the 2 m and IRAC images of outflow structures. The diffuse PDR models [26] are found to deviate from observed ISM colors by about 0.5mag.

5. ACKNOWLEDGMENTS

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