INFRARED EMISSION FROM CLUSTERS IN THE STAR-FORMING DISK OF HENIZE 2-10

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Received 2001 March 21; accepted 2001 May 23

ABSTRACT

We have made subarcsecond-resolution images of the central 10" of the Wolf-Rayet dwarf galaxy He 2-10 at 11.7 μm, using the Long Wavelength Spectrometer on the Keck I Telescope. The spatial distribution of the infrared emission roughly agrees with that of the rising spectrum radio sources seen by Kobulnicky & Johnson (1999) and confirms that those sources are compact H II regions, rather than supernova remnants or other objects. The infrared sources are more extended than the subarcsecond rising spectrum radio sources, although the entire complex is still less than 5" in extent. On size scales of 1" the infrared and radio emission are in excellent agreement, with each source requiring several hundred to a thousand O stars for excitation. The nebulae lie in a flattened disklike distribution about 240 by 100 pc and provide all of the flux measured by IRAS for the entire galaxy in the 12 μm band; 30% of the total IRAS flux from the galaxy emanates from one 15-30 pc source. In this galaxy, intense star formation, probably triggered by an accretion event, is confined to a central disk, which breaks up into distinct nebulae presumably marking the sites of young super-star clusters.

Key words: galaxies: dwarf — galaxies: individual (He 2-10) — galaxies: starburst — galaxies: star clusters — galaxies: peculiar — radio continuum

1. INTRODUCTION

Henize 2-10 is a dwarf elliptical galaxy with a starburst nucleus, and it was the first Wolf-Rayet galaxy identified. Gas motions in and around He 2-10 suggest that it is in an advanced stage of accretion, which may be the trigger for the starburst (Kobulnicky et al. 1995). He 2-10 differs from most dwarf starburst galaxies in that it has at least solar (Conti & Vacca 1994) to twice solar (Beck et al. 1997) metal abundances and is relatively rich in molecular gas. Single-dish radio continuum fluxes of the galaxy as a whole have the nonthermal spectral index of −0.56 (Kobulnicky & Johnson 1999), similar to spiral galaxies and much steeper than most dwarf starbursts. Its distance is determined only to be between 6 and 14 Mpc; we will use 9 Mpc here.

The starburst in He 2-10 takes the form of a disk 5"–8" in length and 2"–3" in height. Conti & Vacca (1994) found optical and UV super-star clusters lying in this disk, and Beck et al. (1997) showed that the near-infrared J, H, and K emission traces it. The disk is perpendicular to the bipolar outflow of ionized gas described in Mendez et al. (1999) and to the apparent angle of the in-falling molecular gas (Kobulnicky et al. 1995; Meier et al. 2001). Kobulnicky & Johnson (1999) measured the radio continuum at 6 and 2 cm with subarcsecond resolution and found the same disk-like structure breaks up into six subsources, five of which are strong enough to be fitted and analyzed individually and all of which are stronger at 2 cm than at 6 cm. A rising spectrum can be the sign of a radio source that is at least partly optically thick at the longer wavelength.

Kobulnicky & Johnson (1999) concluded that the rising spectrum sources are probably giant H II regions excited by hundreds of O stars and containing such dense gas that their intrinsically thermal (Sν = v−0.7) spectrum has been distorted by optical depth effects. Such sources have been seen in NGC 5253 (Turner, Ho, & Beck 1998; Turner et al. 2000) and NGC 4214 (Beck et al. 2001). Near-flat or rising radio spectra are also seen, however, in nonthermal sources not excited by young stars, including active galactic nuclei (AGNs) and supernova remnants (SNRs). The best test for the presence of young stars is the infrared flux: H II regions will have strong and predictable IR emission, and the other candidates will not (Gorjian et al. 2001). It is a particularly good way to weed out SNRs, which are weak IR emitters but strong radio emitters and often present in large numbers in starburst regions. The infrared is also the wavelength of choice for probing star formation regions in general, and it can be expected to be particularly useful in He 2-10, where the radio and optical appearance, although similar in outline, differ greatly in detail and where the optical extinction is known to be very high (Beck et al. 1997). Sauvage et al. (1997) imaged He 2-10 in the mid-IR with 1.1 resolution at the Canada-France-Hawaii Telescope; their raw images at 11.7 μm show two main IR sources possibly associated with four of the five images; deconvolution reveals a possible third, weaker source to the east of the main emission. To better match the resolution of the radio observations, we have accordingly obtained high-resolution (~0.3) mid-infrared (11.7 μm) images of the central disk in He 2-10 using the Long Wavelength Spectrometer (LWS; Jones & Puettter 1993) on the Keck I Telescope. We describe the observations and results in the next section and discuss the peculiarities of He 2-10 in § 3.

2. OBSERVATIONS AND RESULTS

2.1. The Infrared Observations

He 2-10 was observed on 2000 February 17 at the Keck I
based on the FWHM of the standard stars, is to 15% conservatively estimate the error in the total fluxes assigned to each source to be about 10% or lower over time spans of an hour, but showed jumps of 18% over longer periods. The calibration is further complicated by characteristics of the chip. The pixel size is close enough to the size of the source that it is very difficult to find and subtract the sky background, a problem complicated by fringing at the edge of the chip and significant pixel-to-pixel variations in the noise. For these reasons we

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2.2. The Infrared Sources: Luminous and Dense H II Regions in a Disk

The infrared image of He 2-10 shows three sources in a roughly east-west line. The eastern and western infrared sources are individually extended east-west also, following the five smaller radio knots seen by Kobulnicky & Johnson (1999). We will therefore treat the infrared sources as emitted by three sources, which, from east to west, we call A, including radio knots 4 and 5; B, which corresponds to radio knot 3; and C, which includes radio knots 1 and 2. In Table 1 we give the infrared flux of each extended source, along with the radio flux for the region measured from the 2 cm map for the extended infrared region and the ratio of radio to infrared emission. Our 2 cm fluxes are those of the entire extended source and therefore larger than those of the resulting image is shown with the 2 cm radio contours (kindly provided by H. A. Kobulnicky) superposed. Since the absolute registration of the infrared image is good only to about 1 arcmin and the chip is 128 × 128, and the resulting 10′ field is close enough to the size of the source that it is very difficult to find and subtract the sky background, a problem complicated by fringing at the edge of the chip and significant pixel-to-pixel variations in the noise. For these reasons we conservatively estimate the error in the total fluxes assigned to each source to be 15%–20%. The angular resolution, based on the FWHM of the standard stars, is 0.′3 to 0.′5. Two exposures of 216 on-source seconds each were obtained of He 2-10; they were added with no smoothing and the resulting image, rotated to the conventional NUEL orientation, is shown in Figure 1 (left). On the right, the infrared image is shown with the 2 cm radio contours (kindly provided by H. A. Kobulnicky) superposed. Since the absolute registration of the infrared image is good only to about 1″ the superposition was adjusted by eye.

| TABLE 1 | OBSERVED AND DERIVED CLUSTER PARAMETERS |
|----------------|-----------------|-----------------|-----------------|
| Infrared Source | A    | B    | C    |
| Radio equivalent | 4 and 5 | 3    | 1 and 2 |
| 11.7 μm flux (Jy) | 0.59  | 0.07 | 0.22 |
| 2 cm flux (mJy) | 7.27  | 0.89 | 2.76 |
| IR/2 cm | 81    | 77   | 80   |
| L_{IR} (120 K) | 1.7 × 10^9 | 2.1 × 10^8 | 6.5 × 10^7 |
| L_{IR} (1.25 μm) | 4.1 × 10^9 | 5.0 × 10^8 | 1.4 × 10^9 |
| O7 stars (radio) | 5300  | 650  | 2000 |
| O7 stars (IR) | 8500  | 1000 | 3300 |

Kobulnicky & Johnson (1999), which were obtained by fitting Gaussian sources to the central cores of the nebulae. The mid-infrared fluxes we obtain are in good agreement with those observed at lower resolution by Sauvage et al. (1997), although we find that the infrared sources are more extended than predicted by their deconvolution routines and slightly higher than the values found by Telesco, Dressel, & Wolstencroft (1993).

The ratio of infrared to thermal radio flux from an H II region depends on the type and temperature of the dust. Lyman α dust heating alone gives a ratio of 10, but the value usually observed in starburst galaxies and Galactic star formation regions is between 120–250, the excess generally due to dust heating by longer wavelengths and optical depth effects in the radio. From Table 1 we see that all the sources in He 2-10 with values ~ 80 are definitely in the regime of H II regions and not, for example, SNRs, whose infrared fluxes are many orders of magnitude weaker. This confirms...
the identification of the radio sources as compact H II regions (Kobulnicky & Johnson 1999). The relative fluxes of all three components are identical in the radio and infrared: 67% of the flux is in component A, 8% in B, and 22% in C.

While the infrared and radio emission in the three components agree over size scales of \(\sim 1\)\,", their distribution is different in detail. The radio emission is more compact than the infrared. The radio sources have cores of \(\sim 0.1-0.5\) (Kobulnicky & Johnson 1999) surrounded by flatter extended halos, so that the total sizes are similar to the infrared. The infrared sources are larger; when deconvolved from the 0.3\, to \(\sim 0.5\) PSF, component A is \(\sim 0.9 \times 0.5\) or \(40 \times 20\) pc, B is \(\sim 0.3\) or 13 pc, and C is \(\sim 0.5\) (22 pc). The radio beam is about twice as large as the infrared north-south and slightly larger east-west, yet the radio sources appear more compact, and the infrared sources do not have the core and background structure of the radio.

A remarkable result from the infrared image is that the clumpy disk appears, within the uncertainties, to provide at least 80% of the total flux seen by IRAS at 12 \(\mu\)m with a beam that included the entire galaxy. This total is that of the five clumps together; we do not see an extended smooth infrared component. He 2-10 is another case (like NGC 5253; Turner et al. 2000) of a starburst dwarf in which the great majority of OB star formation is concentrated in a small volume; but unlike NGC 5253 the star formation activity is not in a single supercluster but in a much more complex geometry. If we fit a modified blackbody spectrum with \(n \sim 1.5\) to our 11.7 \(\mu\)m and IRAS fluxes, the observed 11.7, 12, and 25 \(\mu\)m fluxes can be fitted with a 120 K source. This 120 K source would account for most of the IRAS 12 and 25 \(\mu\)m flux and thus 40% of the total IRAS luminosity of \(L_{IR} = 6.2 \times 10^8 L_\odot\).

Using a reference OB star luminosity of \(2.5 \times 10^5 L_\odot\) for an O7 star, we calculate the OB star content of each infrared source from its mid-infrared luminosity as listed in Table 1. We also list the OB star content derived from the radio fluxes, using the assumption that they are optically thin (Turner & Ho 1994). If the H II regions have optically thick components, or if dust absorbs a significant number of the photons, then this will be an underestimate of the number of massive young stars. Note that the numbers of OB stars found for the three components based on these two very different methods for the radio and infrared agree very well. The mid-infrared luminosities of regions A, B, and C agree with the ionization requirements of the radio knots, which argues that the radio emission cannot be very optically thick on these size scales. The rising radio spectra must be attributed only to the central cores of the nebula.

The radio/infrared sources contain very dense gas, as Kobulnicky & Johnson (1999) calculated from the radio optical depths, and a great deal of dust to account for their high extinction and infrared flux, and they must therefore be very young. If one estimates a dynamical age based on the time it would take them to expand to the stage of having a normal radio spectrum, one obtains ages of 500,000 yr (Kobulnicky & Johnson 1999). However this assumes that there are no other forces working against their expansion. The apparent contradiction between the very short dynamical lifetimes of compact H II regions and their ubiquity has been reviewed by Kurtz et al. (2000). The possible confinement mechanisms suggested for NGC 5253 by Turner et al. (2000); Gorjian et al. (2001) (i.e., magnetic fields of the milligauss level, gravity) may also be at work in He 2-10. In the case of He 2-10, the more traditional suggestion of confinement by dense molecular gas is also a viable source of extra overpressure, which can keep the nebulae confined and the gas density high.

The age of the He 2-10 nebulae can be estimated independently from the mid-infrared line spectrum of Beck et al. (1997) and the ionization of a starburst as modeled by Crowther et al. (1999). The models can reproduce the infrared line spectrum if the starburst in He 2-10 is relatively old, from 0.5 to \(2 \times 10^7\) yr (Beck et al. 1997). This is not only much older than the dynamical age, a problem that appears in many other sources; it is as old or older than the super-star clusters observed in the optical and UV in the same galaxy (Johnson et al. 2000). It is very hard to find a physically sensible scenario in which the optically visible star clusters, which have already dispersed their gas and dust, are younger than the infrared and radio sources that are still embedded in gas and dust. It is possible that the age derived from the infrared spectrum is misleading. First, the infrared spectrum may be softened by higher than solar metallicity so the clumps may contain younger and hotter stars than the rather cool ones found by the models. Second, the ages found from these models assume that the burst formed with very massive stars present and that the soft ionization currently observed means that stars more massive than 35 \(M_\odot\) have disappeared. The models cannot at present distinguish between a burst of \(5 \times 10^6\) to \(2 \times 10^7\) yr with an initial upper mass cutoff of 60 \(M_\odot\) and a much younger burst whose initial mass function did not extend past 35 \(M_\odot\) to begin with. Mid-infrared diagnostics of stellar age are greatly needed, as only in the mid-infrared can these very young and obscured H II regions be observed properly. We can only conclude that, while these compact nebulae are doubtless the youngest part of the starburst, their age cannot be determined to better than a factor of 10.

2.3. Accretion-induced Star Formation throughout a Dwarf Galaxy Disk?

The high-resolution radio, infrared, and optical observations of He 2-10 find an extended disk that contains or is made out of many clumps, probably star clusters, some of which can be seen in the optical and the others only at the longer wavelengths. Other dwarf galaxies are known to contain intense and small infrared and radio clumps excited by the youngest star clusters, but they have either only one young, embedded cluster (NGC 5253) or a few clusters with no clear underlying structure (NGC 4214; Beck et al. 2001). He 2-10 is so far unique among dwarf galaxies in that its youngest star clusters are associated with a disk. The cluster distribution in He 2-10 is in fact reminiscent of that seen in spiral starburst galaxies, such as NGC 253. Why is He 2-10 so different from other galaxies of its apparent class? We note that the extent of the "disk" (or linear structure) is \(\sim 200\) pc, possibly more if there is significant extension in the line of sight, which corresponds to a sound-crossing time of at least \(\sim 2 \times 10^8\) yr. This is far greater than the inferred ages of the compact H II regions and suggests a star formation trigger. The infrared structure may reflect the rotating molecular gas disk whose morphology and kinematics are described by Kobulnicky et al. (1995). If molecular gas accretes onto a galaxy with a rotating disk, it will not matter where or at what angle it starts; it quickly ends up falling onto the disk. So the accretion-induced star formation will be concentrated in the disk, where local conditions
and perhaps self-gravity structures will determine the size and nature of the star clusters that will form.

Another feature of He 2-10 that differs from the usual dwarf starburst galaxy is its metal content, which is around twice solar (from the Ne II flux observed by Beck et al. 1997), rather than the approximately 0.1 solar seen in NGC 5253, II Zw 40, and many others. This may have an effect on the future evolution of the observed infrared star clusters. Young stars have violent mass-outflow episodes, which can partly disrupt a cluster, and these winds are stronger at higher metallicity. We speculate that the clusters in the disk of He 2-10 will in a few tens or hundreds of megayears be too small and faint to be true globular clusters. Even without the effect of winds it is hard to tell what kind of clusters these sources will become because of the relatively low spatial resolution we have at the distance of He 2-10. Source A, for example, contains about twice as many OB stars as does the supercluster in NGC 5253 (Turner et al. 2000), more than enough stars to evolve into a globular cluster. But we do not yet know if it contains more sub-sources than the two already seen and what the volumes and stellar densities will be.

3. CONCLUSIONS

Mid-infrared images of the dwarf starburst galaxy He 2-10 were obtained with the LWS on the Keck I Telescope. The images show infrared clumps along the galaxy disk, which coincide with the rising spectrum radio sources seen by Kobulnicky & Johnson (1999). The image shows that the mid-infrared emission is more extended than the radio emission, but is otherwise in excellent agreement. This confirms that the sources are compact H II regions excited by large and extremely young super-star clusters. At least 80% of the mid-infrared flux of the galaxy as seen in IRAS comes from the vicinity of these compact nebulae, which extend over 200 × 100 pc and which emit ~40% of the total infrared luminosity of the galaxy. He 2-10 is another example of a starburst galaxy where the current star formation activity is very intense and confined to a very small volume. We suggest that the disk is the site of the starburst because that is where the accreted molecular gas is falling, triggering the burst. We also suggest that, because of the high metal content, the clusters are unlikely to survive the 10 Gyr to become true globulars.

This work was supported in part by NSF grant AST-00 71276 and a COR grant from the UCLA Academic Senate to J. L. T. and by the Israel Academy Center for Multi-Wavelength Astronomy grant to S. C. B. We thank H. A. Kobulnicky for the cm radio map.

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