The Astrophysical Journal, 492:L177–L179, 1998 January 10

NGC 2264 IRS: EVIDENCE FOR TRIGGERED STAR FORMATION

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Received 1997 July 24; accepted 1997 October 30; published 1997 December 30

ABSTRACT

As part of its commissioning process the Near-Infrared Camera and Multiobject Spectrometer (NICMOS) obtained images of the infrared source NGC 2264 IRS, also known as Allen's source, in three colors . In addition to the completely overexposed image of IRS there are six point objects, never previously observed, at projected separations of 2″.6 to 4″.9 from IRS. These sources are interpreted as near solar mass, pre–main-sequence stars that may be the result of triggered star formation. Regardless of the star formation method, it appears certain that this group of stars is a coeval formation of various mass stars. This makes it a very valuable data set for the study of pre–main-sequence evolution.

Subject headings: ISM: jets and outflows — stars: formation

1. INTRODUCTION

The concept of "triggered" star formation is star formation aided or induced by an increase in gas pressure and density due to stellar wind or radiation pressure from another, usually massive, object (Elmegreen 1980; Klein, Whitaker, & Sandford 1985; Cameron, Vanhala, & Hoflich 1998). In general, the massive object is a supernova, but any object with enough luminosity to alter the distribution of matter around it is a candidate for the "trigger" in the system. In this case the trigger is the object NGC 2264 IRS or Allen's source (Allen 1972). The evidence is the close spatial association with NGC 2264 IRS and the distribution of the objects in an arc on one side of NGC 2264 IRS. The arrangement is suggestive of a high-pressure front or shock wave created by the trigger. Allen (1972) pointed out that this object is the likely source of the radiation pressure creating the well-known Cone Nebula since it is the brightest and most luminous object in the field. In addition, the outflow lines projected back from the Cone Nebula converge at the location of Allen's source. Under the usual assumption that the most massive object, Allen's source, formed first the other stars must be coeval to about 10^3–10^4 yr, otherwise the outflow from Allen's source would have removed most of the star formation material on that timescale.

2. OBSERVATIONS

The NICMOS observations of NGC 2264 IRS utilized camera 2 with the F110W, F160W, and F222M filters centered at 1.1, 1.6, and 2.22 μm, respectively. (See Thompson et al. 1998 for details on the NICMOS instrument.) There are nine 32 s integrations in each filter on a 3 × 3 spatial grid at a separation of 0″.27. The Multi-Accum sampling sequence was STEP8 with NSAMP = 10. This results in 10 readouts of the detector spaced at times of 0.0, 0.303, 0.606, 0.995, 1.993, 3.987, 7.981, 15.975, 23.969, and 31.969 s. The readouts are nondestructive, with the first read referred to as zero. There are also 10 blank filter or dark integrations utilizing the same sequence. Nine F222M filter images on a 1″.3 grid measured the thermal background. The epoch of the observations is JD 50566, 1997 April 28.

3. DATA REDUCTION

Data processing of the images utilized a combination of IDL procedures and FLC scripts. FLC (FITS list calculator) is an IDL-based system for creating, manipulating, and performing calculations on the large lists of data files created by NICMOS *HST* observations (Stobie & Lytle 1998). The first two Multi-Accum observations have slightly elevated average counts and slightly altered distributions of these counts across the array. For this reason the dark and image manipulations separate out the first two images from the subsequent Multi-Accum images. In the case of spatial dithering, images after the first image have more delay between integrations than nondithered images. As a consequence, they have a dark count spatial distribution intermediate between the first and second integrations in a non dithered sequence. For these data the first image in each dither sequence has the first dark integration subtracted from it. Subsequent images have an average between the first and second darks subtracted. This was also done with the background images. A median of the background images was then subtracted from the F222M images to remove thermal background. The F110W and F160W have low enough backgrounds that background subtraction is not required.

After correction for the dark, background, and bad pixel effects, the images were cleaned of cosmic rays by an IDL-based procedure. The procedure looks for individual pixels that exceeded a threshold above the surrounding pixels and sudden jumps in signal level between nondestructive reads in the Multi-Accum integrations.

Every pixel in each image was checked for nonlinearity using the individual pixel linearity response functions developed in the preflight testing of NICMOS. Those pixels that were in the nonlinear but correctable region were corrected. The majority of the pixels in the first two Airy rings of the F160W and F222M filters for Allen's source were uncorrectable, yielding no photometric information. The central region of Allen's source saturated even before the first read in the Multi-Accum sequence. Flat-field correction utilized flats obtained during a very early filter-wheel test during flight. These flats are accurate to about 5%, which is more accurate than the errors caused by the presence of the NGC 2264 IRS diffraction pattern. Figure 1 (Plate L53) shows the combined color image of the three filters. This image is a stretched image with the pixel values in each of the three filters raised to the exponent of 0.1 to make the faint companion stars easily visible.

The strong diffraction pattern from NGC 2264 IRS obviously hampers photometry of the companion stars, negating aperture photometry. Roughly concurrent observations of Arp 220 included observations of a bright star in each of the three filters

TABLE 1
PROPERTIES OF THE COMPANION STARS

Object	Arcsec	AU	1.1 Mag[a]	H Mag	K Mag
1 ……	4.9	3740	21.7[b]	17.5	14.9
2 ……	5.2	3940	21.7	16.2	13.0
3 ……	3.6	2740	20.0	15.9	14.2
4 ……	3.8	2910	20.7	16.0	13.3
5 ……	4.5	3400	22.9[b]	16.8	12.5
6 ……	2.6	1990	22.9[b]	16.3	12.6

[a] "1.1 Mag" refers to the magnitude in the F110W filter in the Arizona system with an A0 V star having zero color.
[b] These values are upper limits.

for determination of the point spread function (PSF). Calibrated photometry was done on this star; then scaled intensity images of these PSF observations were subtracted from the six sources in the current observation. The scaling for each source was adjusted until only the IRS diffraction pattern and background were visible. Experimentation showed that scaling changes of 10% are easily visible, generating an obvious source or hole in the background. The photometry of the sources not in the diffraction spikes is accurate to 10% in the H and K bands. In some cases there are only upper limits to the F110W flux. The two sources (2 and 6) coincident with the spider diffraction spikes have about 15% accuracy. Table 1 gives photometric and spatial information on the six sources.

4. NATURE OF THE SOURCES

A normal procedure in star formation regions is to plot the sources in a color-color plot and place them in a computed evolutionary sequence. However, most computed evolutionary sequences utilize a gray atmosphere assumption that even the authors warn against using (D'Antona & Mazzitelli 1994). In general, observations of pre–main-sequence objects find very nonstellar colors due to the presence of disks, associated dust, and outflows (Adams, Lada, & Shu 1987). Allen's source itself is a prime example with a very nonstellar spectral energy distribution (Chini, Krugel, & Kreysa 1986). For this reason we will not try to place the companion stars on a theoretical temperature luminosity track.

4.1. *Allen's Source*

As has been noted previously (Thompson & Tokunaga 1978), the exact nature of NGC 2264 IRS is ambiguous. Its luminosity of $2.3 \times 10^3\ L_\odot$ is consistent with a ZAMS B2 star, however, its K magnitude of 4.88 (Allen 1972) is far too bright for a B2 star, even in the absence of extinction. For reasons that will be discussed later we will revise the extinction from the A_V-value of 35 used in Thompson & Tokunaga (1978) to a value of 20. With this extinction, the N_e^2V-value is consistent with a B0.2 star if only the Lyman continuum ionization is considered or with B8 if the Balmer continuum is also utilized. The luminosity and ionization are consistent with an intermediate value typical of line excess sources that produce partial ionization from the $n = 2$ state (Thompson 1984). The excess K brightness is very probably due to the presence of a luminous viscous disk or free-free emission from the very high-density ionization region implied by the line excess. The line excess requires a very strong outflow from the source even at the current time.

4.2. *The Companion Sources*

The $H - K$ colors of the companion sources are consistent with very young, highly reddened sources of type a or b of Adams et al. (1987). If we assume that all of the sources have similar extinction, we can impose a criterion that the $H - K$ color must be positive. The highest extinction that preserves this criterion is $A_V = 20$. This extinction value is not high enough to satisfy the condition that Allen's source must have an I magnitude fainter than 20. However, given the uncertainties in the slope of the extinction function in the I band, we adopt 20 as a reasonable number for the region. Table 2 gives the dereddened and absolute magnitudes of the sources for that extinction. The very red colors of all of the sources except source 3 confirm that the companion stars do not have normal stellar colors but are consistent with the range of $H - K$ colors from 0.4 to 3.1 found in the flat spectrum sources of Adams et al. (1987).

Table 2 gives two estimates of the luminosity of the companion sources. The first estimate assumes that the spectral energy distribution of the companion sources is similar to Allen's source and scales the Allen's source luminosity by the ratio of the observed K fluxes. The second method assumes that all of the sources have the spectrum of a K7 dwarf and that the dereddened K flux is the photospheric flux.

An estimate of the masses of the companion objects is possible using the luminosity estimates, an evolutionary time, and the tables in D'Antona & Mazzitelli (1994). In Table 2 the last column shows the estimated mass from the luminosity based on Allen's source and an evolutionary time of 1.5×10^5 yr. The evolutionary time is equal to the time needed for Allen's source to traverse the radiative equilibrium track and reach the zero-age main sequence (ZAMS) (Iben 1965). The masses range between 0.12 and 0.42 $M_\odot$, with a total mass in the companion stars of 1.74 $M_\odot$.

5. TRIGGERED OR UNASSISTED FORMATION?

A viable alternative to triggered or assisted star formation is previous or coeval formation unaffected by NGC 2264 IRS. Also, we must consider the possibility that the observed objects are just chance groupings of stars not physically associated

TABLE 2
INTRINSIC MAGNITUDES AND COLORS OF THE COMPANION STARS WITH $A_V = 20$

Object	1.1 Mag	H	K	Abs 1.1[a]	Abs H	Abs K	$H - K$	$L_\odot$[b]	$L_\odot$[c]	$M_\odot$
1 ……	14.9	14.1	13.0	5.5	4.7	3.6	1.1	0.2	0.3	0.12
2 ……	14.9	12.8	11.1	5.5	3.4	1.7	1.7	1.3	1.6	0.33
3 ……	13.2	12.5	12.3	3.8	3.1	2.9	0.2	0.4	0.6	0.19
4 ……	13.9	12.6	11.4	4.5	3.2	2.0	1.2	1.0	1.3	0.28
5 ……	16.1	13.4	10.6	6.7	4.0	1.2	2.8	2.1	2.5	0.42
6 ……	16.1	12.9	10.7	6.7	3.5	1.3	2.2	1.9	2.5	0.40

[a] The absolute luminosity uses a distance of 760 pc (Hodapp 1994).
[b] The luminosity calculated by the ratio of K fluxes times the luminosity of Allen's source.
[c] The luminosity calculated by assuming a K7 dwarf color.

with each other. In the following we investigate each of these possibilities.

5.1. *Chance Association*

The extremely red colors of the six stars leaves little doubt that they are not foreground K or M dwarfs. The colors are consistent with the extinction suffered by the central source, which puts the stars either in or behind the molecular cloud. From a count of all objects, foreground and background, in the CD-ROM data of Hodapp (1994) there is a source density of 11.8 sources per square arcmin to a limiting K magnitude of 16 in the immediate vicinity of NGC 2264 IRS. This makes the probability of having the six sources within 1.6×10^{-2} arcmin^2 of the central source 4.4×10^{-5}. From this probability we will assume that the stars are physically associated with the central source. The possibility that the objects are optical ghosts from Allen's source can be dismissed since the sources have a sharp focus and other highly saturated observations such as BN in Stolovy et al. (1998) do not show objects at the same locations relative to the central star.

5.2. *Triggered Star Formation or Untriggered Coeval*

The close association of the six stars with four stars roughly at equal distances from central source make a seductive visual argument that the presence of this strong outflow source triggered the formation of the these stars. If we assume that the most massive object in the core, Allen's source, forms first, then the remaining stars must form within about 2000 yr of the onset of the outflow assuming a typical outflow velocity of 10 km s^{-1} and a distance of 4000 AU. After that time most of the material needed to form new stars would have been swept away. This timescale argues strongly for the concept of triggered star formation.

The presence of a B2 ZAMS star indicates that the dark core of the molecular cloud that formed the system was very dense. The mass of the six companion stars represents only about 15% of the total stellar mass present in the system. The basic conclusion is that if there was enough mass to form the approximately 9.5 $M_\odot$ B2 star, there was sufficient mass left over to form the other stars. Also the very dense nature of the core needed to form the B2 star should have put the rest of the core near the critical density to form other stars. If the B star material came from inside a radius of 2000 AU, the minimum density would be about 3×10^8. Allowing for inefficient star formation and the formation of the other stars a density of about $n = 10^{10}$ cm^{-3} appears reasonable. The work of Elmegreen (1994) shows that the collapse time is equal to $(G\rho)^{-1/2}$, which is $10^8 n^{-1/2}$ yr. A density of 10^{10} then produces a collapse time of 10^3 yr, which is consistent with the outflow timescale discussed above. A previous high density is implied by the current density in the region of $\sim 2 \times 10^6$ cm^{-3} (Schreyer et al. 1997), which has been reduced from the initial density by the outflow.

5.3. *Timescales and Dynamics*

An interesting question about the system is why the companion stars are still so closely associated with Allen's source and roughly arranged in an arc on one side. With the masses assumed in the above work the virial velocity at 4000 AU is 0.3 km s^{-1} and the crossing time of the system is 1.2×10^5 yr. This is roughly compatible with the evolutionary time of 1.5×10^5 yr. A possible scenario is that the star-forming mass was distributed in a Keplerian disk around Allen's source. If the actual distance is somewhat greater than the projected distance, there may not yet have been enough time for the stars to have completed one orbit and are still relatively closely bunched together. One needs to note that there may be other companion sources to the north of Allen's source that fall out of the field of view.

6. FUTURE WORK

The brightness of NGC 2264 IRS ($K = 4.88$) makes it an ideal candidate for adaptive optics investigations with large telescopes, especially if the adaptive optics are used in conjunction with a small aperture spectrometer to obtain spectral information on the lower luminosity objects. Future work with *HST* should include images at a different roll angle to move the diffraction pattern and coronagraphic imaging in the Pα and H_2 as well as continuum filters.

The authors gratefully acknowledge the work done on the observing proposal by Edward Bergeron and Abhijit Saha. R. I. T. also thanks A. G. W. Cameron and B. Elmegreen for extremely useful discussions on triggered star formation. This work is supported in part by NASA grant NAG 5-3042. This Letter is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

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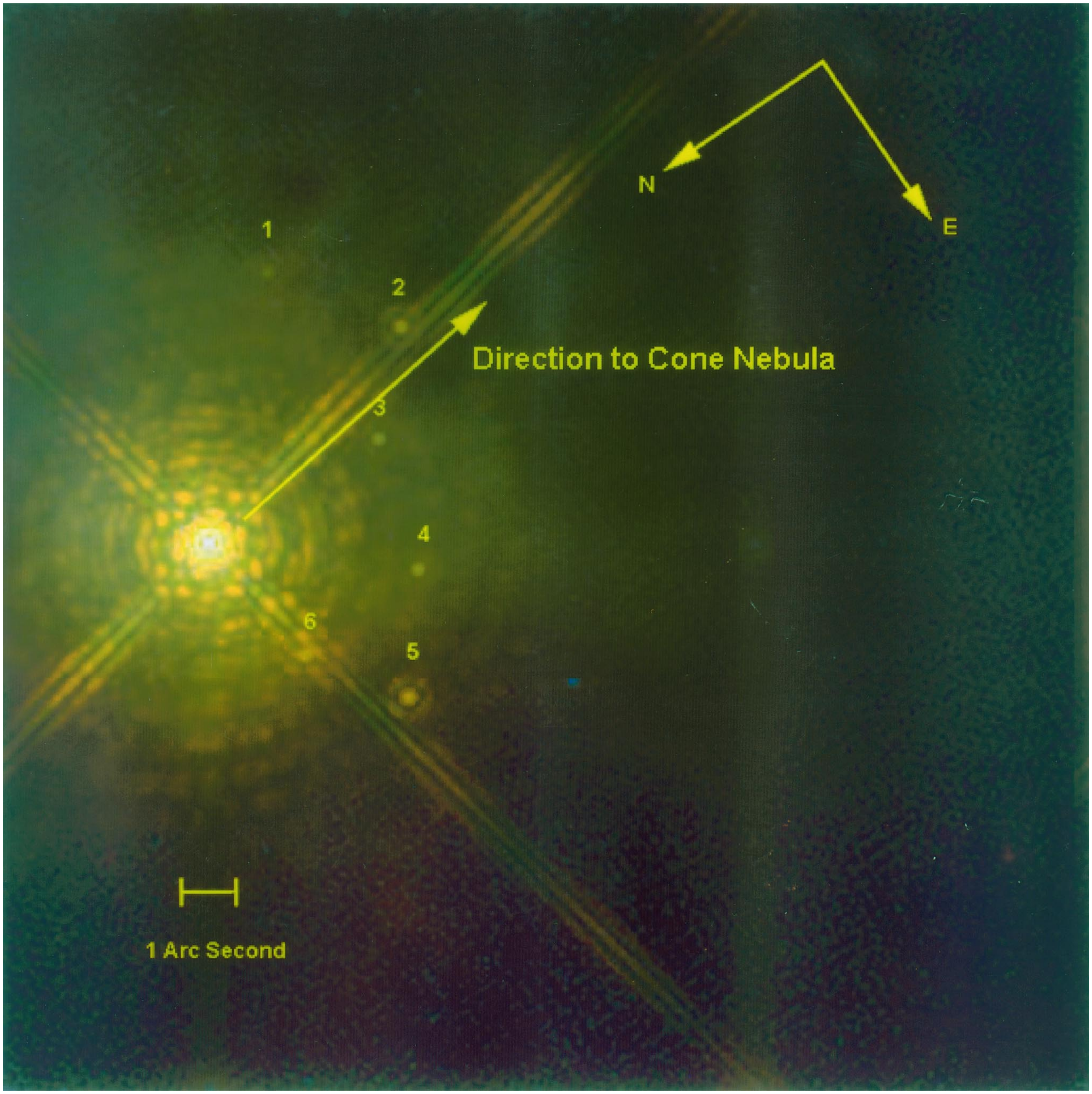

FIG. 1.—This is a three-color plate of NGC 2264 IRS and its companion stars. The intense saturated source is NGC 2264 IRS located at (J2000) R.A. = $06^{h}41^{m}10^{s}.1$, Decl. = $+09°29'34''$. See the text for a description of the plate.