A MASSIVE-STAR-FORMING INFRARED LOOP AROUND THE CRAB-LIKE SUPERNova REMNANT G54.1+0.3: POST–MAIN-SEQUENCE TRIGGERED STAR FORMATION?

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ABSTRACT

We report the discovery of a star-forming loop around the young, Crab-like supernova remnant (SNR) G54.1+0.3 using the AKARI infrared satellite. The loop consists of at least 11 young stellar objects (YSOs) embedded in a ringlike diffuse emission of radius ≈1′. The YSOs are bright in the mid-infrared and are also visible in the Spitzer Space Telescope Galactic plane survey images. Their Spitzer colors are similar to those of Class II YSOs in [3.6] − [5.8] but significantly redder in [8] − [24], i.e., 0 < [3.6] − [5.8] < 1.2 and 5 < [8] − [24] < 9. Most of them have near-infrared counterparts in the 2MASS JHK, images, and some of them have an optical counterpart too. Their JHK colors and magnitudes indicate that the YSOs are massive (≥10 M⊙) pre–main-sequence stars at the same distance to the SNR, i.e., 8 kpc, which supports the association of the star-forming loop with the SNR. The dereddened spectral energy distributions are similar to early Herbig Be stars, which are early B type pre–main-sequence stars with inner disks that have been destroyed. The confinement to a loop structure indicates that the YSOs are young, i.e., ≲2 Myr. We propose that their formation is triggered by the progenitor star of G54.1+0.3, which has a mass of ≈15 M⊙. The triggering must have occurred near the end of the progenitor’s life, possibly after it had evolved off the main sequence.

Subject headings: infrared: stars — ISM: individual (G54.1+0.3) — stars: formation — stars: pre–main-sequence — supernova remnants — supernovae: general

1. INTRODUCTION

Massive stars can trigger the formation of a next generation of stars. Their strong stellar ultraviolet radiation and winds can compress the ambient medium so that it becomes gravitationally unstable and collapses. Numerous examples supporting the scenario of triggered star formation have been proposed, from young stars formed in small bright-rimmed globules inside H ii regions to OB associations around kiloparsec supershells (see Elmegreen 2002; Zinnecker & Yorke 2007 and references therein).

In this Letter, we report the discovery of a unique example of triggered star formation, namely triggering by the progenitor star of a young, core-collapse SNR. The SNR (G54.1+0.3) is Crab-like, with centrally brightened synchrotron emission in radio and X-rays (Velusamy & Becker 1988; Lu et al. 2002). The extent of the remnant is 120′′ × 80′′ and is much fainter than the Crab, e.g., 0.5 Jy versus 1040 Jy at 1 GHz. At the center, a 136 ms radio/X-ray pulsar with a characteristic age of 2900 yr has been discovered (Lu et al. 2002). The distance to the SNR is 8 kpc (§ 4). This object provides a laboratory in which to explore the physics of triggered star formation.

2. DISCOVERY OF THE IR LOOP

A mid-infrared (MIR) observation of G54.1+0.3 was done using the Infrared Camera (IRC) aboard AKARI on 2007 April 17. The observation was performed in a framework of the AKARI mission program: the ISM in our Galaxy and nearby galaxies (ID: 1401070.1, PI: H. K.) The IRC is equipped with three wave band channels covering the 2.6–26 μm wavelength range with a 10′′ × 10′′ field of view (FOV) (Onaka et al. 2007). We used the MIR-L channel in IRC02 mode, which gave two band images, L15 and L24, centered at wavelengths of 15.58 and 22.89 μm, respectively. Their angular resolutions are 5.7′′ (L15) and 6.8′′ (L24). The total on-source integration time was 196 s for each band. The basic calibration and data handling were processed using the standard IRC Imaging Data Reduction Pipeline version 070104. The positional uncertainty is 0.15′′ at the 1 σ confidence level.

Figure 1 shows the AKARI L15 image of G54.1+0.3 with the 4.85 GHz radio continuum image overlaid. The radio image was made from archive data of the Very Large Array (VLA) of the National Radio Astronomy Observatory; the data were originally obtained by Velusamy & Becker (1988). The AKARI image shows a well-defined, bright, ringlike structure at the position of the SNR (see also Slane 2007). The ring appears partially complete with its northeastern portion opened, with faint ridges extending out from the ends of the bright ring. The bright portion of the ring (hereafter the “main ring”) is elongated along the northwest-southeast direction and has an extent of ∼105′′ × 54′′, or 4.1× 2.1 pc at 8 kpc. The ring is composed of both diffuse and compact sources. Most of the compact sources are pointlike except the bright one at the northwestern end. There are more than 10 point sources distributed along...
the main ring and several others at the “tips” of the faint ridges. Most of them are bright in the 24 μm image and have colors quite different from foreground/background stars. This can be seen in Figure 1 (right), which is a three-color image produced from the Spitzer IRAC 5.8 μm (B), AKARI 15 μm (G), and Spitzer MIPS 24 μm (R) images. We obtained the Spitzer image of the source from the GLIMPSE (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire, Release II) and MIPSGAL legacy projects. There are 11 sources with colors significantly redder than the other stars in the field (see also the inset in Fig. 2).

3. Young Stellar Objects in the IR Loop

We conducted photometry of a 4.5′ radius area surrounding the IR loop using the AKARI 15 and 24 μm and the Spitzer MIPS 24 μm and 70 μm images. We have identified 151 sources detected in at least one of the 15 or 24 μm bands; most of them were detected at 15 μm while 76% were detected at 24 μm. At 70 μm, only one source was identifiable and only upper limits are derived for the rest. The photometry of stars in the IR loop is not straightforward because of the bright diffuse emission from the loop. We did PSF photometry to minimize the contamination due to the diffuse emission. Sources are cross-identified with the Spitzer GLIMPSE catalog, which contains fluxes of the four IRAC bands, and also with the 2MASS Second Incremental Release Point Source Catalog.

Figure 2 shows the Spitzer [3.6] − [5.8] versus [8] − [24] color-color plot of the 64 sources detected in the IRAC and MIPS 24 μm bands with a [24] magnitude error less than 0.2 mag. The stars clustered near (0.0, 0.0) are probably main-sequence or giant stars along the line of sight. The sources along the IR loop are well defined in this diagram by their strong [8] − [24] excess and moderate or small [3.6] − [5.8] excess, i.e., 5 < [8] − [24] < 9 and 0 < [3.6] − [5.8] < 1.2. The sources within this box are marked by filled circles. The half-filled circles with arrows in the box represent the sources not detected in one of the IRAC 5.8 and 8.0 μm bands but are included because they are likely to fall into the box based on their MIR colors. We marked their positions using a shorter IRAC band; e.g., if a source is not detected at 8.0 μm we used [5.8] instead of [8.0] and placed an arrow. The inset shows that all sources in the box are distributed along the IR loop, although the loop of YSOs is quite distorted. Their colors are different from those of previously studied YSOs in nearby star-forming regions. We show this by drawing boxes (dotted lines) in Figure 2 representing the areas occupied by young embedded protostars with both circumstellar disks and envelopes (Class 0/I) and pre–main-sequence stars with significant circumstellar disks (Class II) determined by previous studies (e.g., Muzerolle et al. 2004). It is clear that the YSOs in the IR loop do not fall into the usual Class 0/I or Class II areas and that this cannot be due to extinction. There are many sources that fall into and around Class II areas. They are outside the IR loop and will not be discussed further in this paper.

Figure 3 (bottom) shows a J − H versus H − K, color-color diagram for all 110 MIR sources identified in the 2MASS JHK bands. The small dots represent sources not detected in Spitzer MIPS 24 μm or IRAC bands while the other symbols have the same meaning as in Figure 2. There are only nine filled/half-filled circles because two YSOs with large [3.6] − [5.8] (Fig. 2) are not identified in the 2MASS bands. The dashed line represents the main sequence (MS), which is from Bessel & Brett (1988) for stars later than A0 and is based on calculations of the JHk colors from Kurucz model atmospheres (Castelli & Kurucz 2003) for stars earlier than A0. The dotted line represents interstellar reddening line of an A0 star following the reddening law of Bessel & Brett (1988). Note that the YSOs are clustered around the positions of reddened OB stars. Another way to see this is from the color-magnitude (K, vs. H − K) diagram (Fig. 3, top). In this diagram, the dashed line represents the MS at 8 kpc calculated from the Kurucz model atmospheres and using the relation between effective temperature and radius of MS stars. We adopt the relation of Martins et al. (2005) for O-type stars and that of Schmidt-Kaler (1982) for stars later than B0. For B0 stars, we interpolate the two
with an adopted temperature of $T_{\text{eff}} = 30,000$ K. The dotted lines represent the reddening lines that bound the YSOs. The YSOs are again clustered around the positions of reddened early-type stars. The YSOs are not aligned along a single MS line, but that may be due to slightly different amounts of extinction toward individual sources. The extinction toward individual objects can be derived if we assume that they are on the MS, and it ranges from $A_v = 6.9$ to 9.2 with a mean of $A_v = 8.0 \pm 0.7$ mag. The mean extinction agrees very well with the extinction implied from the X-ray-absorbing H columns to the SNR, i.e., $A_v = 8.4 \pm 0.5$ mag from $N(H) = 1.6(\pm 0.1) \times 10^{22}$ cm$^{-2}$ (Lu et al. 2002). We conclude that the $JHK_s$ color-color and color-magnitude diagrams are consistent with the YSOs being massive pre–main-sequence stars at 8 kpc. The spectral types determined from their $K_s$ magnitudes in Figure 3 (top) are B1.5 to O8, which have $T_{\text{eff}} = 23,000–35,000$ K, masses of 12–21 $M_\odot$, and luminosities of $(1–10) \times 10^4 L_\odot$.

Figure 4 shows the SED of the most luminous source in the $K_s$ band (the brightest one in the southern part of the loop in Fig. 1) as an example of the YSO SEDs. The filled symbols represent dereddened fluxes using the value $A_v = 6.9$ mag derived from Figure 3 and an interstellar reddening law with $R_v = 3.1$ (Draine 2003). The dereddened SED is characterized by a starlike SED with a MIR/FIR excess at $\geq 8$ $\mu$m, as we could have inferred from Figures 2 and 3. The spectrum at $\leq 5$ $\mu$m matches reasonably well the SED of a 35,000 K MS star, the temperature of which was determined from its $K_s$ magnitude (Fig. 3). This spectrum is quite similar to the SED of early Herbig Be (HBe) stars (spectral type B0–B5; group III) (Hillenbrand et al. 1992; Malfait et al. 1998). A dip at 6–10 $\mu$m similar to that in Figure 4 was observed in HBe stars and has been interpreted as a physical hole in the dust distribution caused by the breakup of inner disks (Malfait et al. 1998). If we consider the MIR/FIR excess at $\geq 8$ $\mu$m to arise from an optically thick disk with a constant effective temperature and fit the SED with a 35,000 K star plus a blackbody, we obtain a disk with a temperature of 190 K and a luminosity of 160 $L_\odot$, although this fit is not quite satisfactory. Most YSOs in the IR loop have SEDs similar to Figure 4, with some objects showing weak MIR excess also. The ratio of the disk to stellar luminosity is $\leq 1\%$, showing that there is not much circumstellar material near the YSOs. If we use the empirical relationship of Nakajima (2005) between stellar masses and $K$ magnitudes for group III HBe stars, the masses of the YSOs range from 12 to 18 $M_\odot$, which agrees with our estimates above. The 2MASS survey has a limiting $K_s$-band sensitivity of 14.3 mag, corresponding to a 6 $M_\odot$ star at 8 kpc with 8 mag of extinction; no additional MIR sources are seen between 13.2 and 14.3 mag in the vicinity of the IR loop, however, which suggests a nonstandard IMF for this region.

4. SNR/IR LOOP ASSOCIATION AND THEIR DISTANCE

The IR loop surrounds the X-ray/radio bright central portion of the SNR almost perfectly. The SNR is somewhat extended along the northeast-southwest direction, suggesting that its expansion has been blocked toward the IR ring. We note that the radio contours are deformed around the northwest peak, which is consistent with encountering a dense medium there. The positional coincidence with a detailed spatial correlation strongly suggests that the IR loop and the SNR G54.1+0.3 are associated. The agreement between the extinction toward the IR loop and the X-ray absorbing column toward the SNR further supports the association (§ 3). The absence of direct evidence for the interaction of the SNR shock with the dense gas may be understood if we assume that the IR loop is a partial shell in a low-density medium, so that the SNR shock has been able to propagate well beyond the loop now.

The distance to G54.1+0.3 has been determined by Camilo et al. (2002), who derived the dispersion measure of the central pulsar (308 cm$^{-3}$ pc) and noted that it corresponded to a distance of 8–12 kpc, depending on the electron-distribution model of the Galaxy. We have obtained an H I absorption spectrum of...
the SNR using the VLA Galactic Plane Survey data (Stil et al. 2006). The H I spectrum of the SNR shows H I absorption over all positive velocities, which indicates that G54.1+0.3 is beyond the tangent point (2.5 kpc). The absorption peak occurs at +23 km s⁻¹, and at this velocity there is a faint ¹³CO J = 1–0 emission coincident with the IR loop in the Boston University–Five College Radio Astronomy Observatory Galactic Ring Survey (Jackson et al. 2006). The emission is weak (T_k ≤ 0.7 K) and implies a mass ≤400 M☉. The kinematic distance corresponding to +23 km s⁻¹ is 8.2 kpc using the rotation curve of Brand & Blitz (1993), who adopt R_⊙ = 8.5 kpc and Ω_⊙ = 220 km s⁻¹. This is consistent with the distance derived from the pulsar DM. We adopt 8 kpc as the distance to G54.1+0.3 and the IR loop, and note that this is the distance to the Perseus spiral arm in this direction.

5. POST–MAIN-SEQUENCE TRIGGERED STAR FORMATION?

The alignment of the YSOs along a small, looplike structure strongly suggests that we are observing star formation triggered by some mechanism originating at the center. It cannot be the SNR G54.1+0.3, however, because the remnant is only a few thousand years old. Instead, the location of the G54.1+0.3 pulsar near the center of the IR loop indicates that it is most likely the progenitor star of the SNR and that the massive progenitor star produced an H II region/wind bubble that compressed the ambient medium into a shell that fragmented and collapsed to form the YSOs.

What is more interesting about this system is that the triggered star formation must have occurred near the end of the progenitor’s life, possibly when it was in its post–main-sequence phase. The ages of early Herbig Be stars are not well known because they usually cannot be estimated from the H-R diagram (e.g., Testi et al. 1998). The surrounding diffuse emission in the IR loop, which might be the emission from dust grains in natal cloud heated either by the YSOs or/and other nearby B stars, indicates that they are young. We can set a limit on the age of the YSOs by noting that 100 M☉ of stars in a region with a radius of 2 pc should have a 1D velocity dispersion of about 0.2 km s⁻¹. In order for these stars to have a regular spacing of about 0.7 pc as observed, they could not have moved more than ~0.35 pc, which sets a limit on their age of about 2 Myr. This limit is significantly shorter than the main-sequence lifetime of the progenitor star: Chevalier (2005) identified G54.1+0.3 as the remnant of a Type IIP SN, with a progenitor mass ~10–25 M☉. The destructive impact of a massive star on the ambient molecular cloud increases rapidly with stellar mass (Chevalier 1999), so the small size of the IR loop and the regular structure seen in the spatial distribution of the YSOs suggest that the progenitor was near the lower end of this mass range. A 15 M☉ star has a lifetime ~13 Myr, and it spends about 10% of its life in the post–main-sequence phase (Schaller et al. 1992). The post–main-sequence lifetime increases for lower stellar masses. Therefore, it is possible that the YSOs formed during the post–main-sequence phase, although it is likely that the progenitor had a significant dynamical effect on the natal cloud while it was still on the main sequence.

We do not have enough information to determine why the triggering was delayed, i.e., why it did not occur during the first few Myr as theories predict (e.g., Hosokawa & Inutsuka 2006). Two possibilities can be ruled out: The triggering was most likely not due to the wind associated with the red supergiant (RSG) phase of evolution, since a typical RSG wind is far too weak to have a significant effect on the shell (Chevalier & Emmering 1989). In any case, the RSG wind in G54.1+0.3 may have been particularly weak since no SNR shock propagating into ambient or circumstellar medium has been detected (Chevalier 2005). One might also think that the temperature and ionization of the ambient molecular gas would drop significantly when the progenitor evolved off the main sequence, but Spaans et al. (1994) showed that the temperature and ionization in molecular gas that is near a star do not vary much for effective temperatures in the range (6–30) × 10³ K. A potential explanation for the delay in the triggering of the star formation is that the natal cloud was shielded by other material until a few Myr ago, when it was exposed to the star by a combination of motion of the star relative to the cloud and photoevaporation of the intervening gas. Future observations will reveal the properties of the newly formed stars and shed light on the triggering of star formation by evolved stars.

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