

The Brightening of Re50N: Accretion Event or Dust Clearing?

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ABSTRACT

The luminous Class I protostar HBC 494, embedded in the Orion A cloud, is associated with a pair of reflection nebulae, Re50 and Re50N, which appeared sometime between 1955 and 1979. We have found that a dramatic brightening of Re50N has taken place sometime between 2006 and 2014. This could result if the embedded source is undergoing a FUor eruption. However, the near-infrared spectrum shows a featureless very red continuum, in contrast to the strong CO bandhead absorption displayed by FUors. Such heavy veiling, and the high luminosity of the protostar, is indicative of strong accretion but seemingly not in the manner of typical FUors. We favor the alternative explanation that the major brightening of Re50N and the simultaneous fading of Re50 is caused by curtains of obscuring material that cast patterns of illumination and shadows across the surface of the molecular cloud. This is likely occurring as an outflow cavity surrounding the embedded protostar breaks through to the surface of the molecular cloud. Several Herbig-Haro objects are found in the region.

Subject headings: stars: formation — stars: low-mass — stars: protostars — stars: pre-main sequence

1. INTRODUCTION

Stars are born deeply embedded in dense cloud cores, which are themselves embedded in larger, more tenuous molecular clouds. As a newborn star gains mass, it forms a circumstellar disk, and perpendicular to the disk the star drives a powerful bipolar outflow. The outflow creates cavities in the molecular surroundings, and when a cavity breaks

through the surface of the surrounding cloud, it allows light to escape from the cloud for the first time. As the cavities expand, the star eventually emerges from its confinement. The first manifestation of the opening of an outflow cavity is the appearance of a compact reflection nebula, as the light of the star floods the surrounding molecular landscape. Such nebulae are commonly found when inspecting the surfaces of dark clouds.

A particularly fine example of a reflection nebula was discovered in the southern L1641 cloud (Reipurth 1985). Examination of Schmidt plates of the region showed that sometime between 1955 and 1979 a bright ~ 1 arcmin wide reflection nebula appeared next to the embedded source IRAS 05380–0728 in the southern part of the Orion A cloud complex. In a more detailed study, Reipurth & Bally (1986) obtained an optical red spectrum of the reflection nebula, showing $H\alpha$ and the Ca triplet in emission. With a luminosity of $\sim 250 L_{\odot}$, the source, labeled HBC 494 by Herbig & Bell (1988), is among the most luminous sources in the L1641 cloud. The nebula has two components, a larger part, Re50, and a highly variable part to the north, Re50N; the latter is associated with the embedded source. A molecular outflow is associated with the source (Reipurth & Bally 1986, Fukui et al. 1986), and has been studied in detail by Lee et al. (2002).

The region has since been explored in a number of studies. Scarrott & Wolstencroft (1988) used optical polarization imaging to identify the location of the source HBC 494, which was subsequently detected as a radio continuum source (VLA 1) by Morgan et al. (1990), and a second radio continuum source VLA 2 was found by Anglada (1995) about an arcminute to the WNW of VLA 1. Casali (1991) determined an extinction of $A_V \sim 50$ mag to the illuminating source whereas Quanz et al. (2007) found $A_V \sim 26$ mag, and Colomé et al. (1996) suggested a total mass of $\sim 3 \times 10^3 M_{\odot}$ within 0.3 pc of the source.

In this paper we document a major recent brightening of Re50N and discuss the possible underlying mechanisms.

2. OBSERVATIONS

The Variable Young Stellar Objects Survey (VYSOS) program employs two robotic telescopes, of which a 20 inch f/8.2 Ritchey-Chretien reflector (VYSOS-20) is used for the observations reported here. The location of the telescope is at Mauna Loa Observatory in Hawaii, at a latitude of 20° and an elevation of 3400m. Imaging is done with an Apogee Alta U16M CCD and the field of view is $30.8' \times 30.8'$ with $0.45''/\text{pixel}$. VYSOS-20 started regular operation in July 2012, with automatic scheduling software to repeatedly ob-

serve selected star forming regions. In November 2013, we noticed an increase of the brightness of Re50N, and started to monitor the target each night. Three exposures of 100 sec are taken in a Sloan i -band filter for each target every night.

The imaging data were calibrated using the Image Reduction and Analysis Facility (IRAF; Tody 1986). Specifically, the aperture photometry was performed using IMEXAMINE in IRAF, and since Re50N is extended an aperture size of $17.8''$ was used to include all the main bright nebulosity. The absolute magnitude scale was established based on reference stars from the Pan-STARRS catalogues (E. Magnier, private communications). The photometric uncertainty is estimated from the Pythagorean sum of the standard errors from each night and an additional calibration error measured using a nearby star.

Five 2-min exposures were made of the Re50 region with the 8 m Subaru telescope and Suprime-Cam on UT January 5, 2006 as part of a survey for new Herbig-Haro objects. A five-point dither map with step size of $40''$ was used in order to cover the $17''$ gaps between the 10 individual CCDs. A [SII] filter was used with an FWHM of 130 \AA , central wavelength of 6714 \AA , and peak transmission of 87%. The seeing was $0.6''$ and the airmass was 1.54.

A second-epoch set of images was obtained at the Gemini-South telescope during Director’s Discretionary Time on March 5 and 7, 2014. Three broadband filters were used, Sloan r' , i' , and z' , and three narrow-band filters, $H\alpha$, [SII], and a filter with similar bandwidth in the continuum between the $H\alpha$ and [SII] filters. Three dithered exposures were obtained in all filters, each exposure was 40 seconds for the broadband filters, and 200 sec for the narrow-band filters. The airmass ranged from 1.26 to 1.48. The narrowband images were taken with a seeing of $0.6''$ and the broadband images with $0.7''$.

We observed Re50N on 2014 January 19 UT with NASA’s Infrared Telescope Facility located on Mauna Kea, HI. We used the facility instrument SpeX (Rayner et al. 1998) to obtain both near-IR images of the region and low-resolution ($R \approx 1200$) spectroscopy of the embedded source. Conditions were photometric with seeing roughly $1''$ but variable as measured by the CFHT seeing monitor. For imaging, we obtained seven dithered

exposures of Re50 and the A0 V star HD 48481 using each of the MKO J, H, and K-band filters. Exposure times for Re50 were 30 sec in J and H-bands, and 5 sec \times 2 coadds in K-band. In addition, we obtained five dithered 60 sec exposures of a nearby empty field in all three filters for sky flats. For the spectroscopy, we used SpeX in SXD mode with the 0.5'' slit. We nodded the point source in Re50 along the slit in an ABBA pattern for four individual exposures of 30 sec each, and two of 120 sec each, for a total exposure time of 6 minutes. Re50 was observed at an airmass of \approx 1.20, with the slit aligned with the parallactic angle to minimize differential chromatic refraction. We contemporaneously observed HD 48481 in SXD mode for telluric calibration.

3. RESULTS

In November 2013 we started to follow the Re50 region with the VYSOS 20-inch telescope observing in the *i*-band (Section 2), and within a few weeks it became obvious that we had caught the object during an unusual episode of brightening. The light curve is shown in Figure 1. It indicates that in late 2013 Re50N was brightening at a rate of \sim 0.01 mag/day. From the middle of January 2014 and until Orion disappeared behind the Sun, the rate slowed significantly. When the region was observed again in September 2014 it was clear that the brightening had reached a plateau.

We do not know when this brightening began, but we observed the region in January 2006 with the Subaru telescope and SuprimeCam in search of Herbig-Haro objects. The image, taken through a [SII] 6717/6731 filter in 0.6'' seeing, is shown in Figure 2a. An identical image from Gemini-South, also taken in 0.6'' seeing, is shown in Figure 2b.

Comparison of the Subaru and Gemini images show that Re50N brightened dramatically between 2006 and 2014. At the same time the main object Re50 has faded greatly. Comparison of the 2014 [SII] image with an identical image taken in the continuum between [SII] and H α does not reveal the presence of any shock-excited emission, the light we see is pure continuum, that is, light reflected from the embedded source.

Figure 3 shows a color mosaic of JHK images, revealing a structured reflection nebulosity seen mainly in the J filter, and the illuminating source

as a single point source detected only in the K-filter, suggesting a significant amount of extinction towards the source. The source corresponds to the previously mentioned VLA 1 source detected in the radio continuum (Morgan et al. 1990, Anglada 1995). A K-band spectrum of this source is seen in Figure 4, revealing a featureless very red continuum. This spectral appearance was already noted by Reipurth & Aspin (1997) from lower-resolution spectroscopy. Such an appearance is in contrast to that of FUors, which show characteristic deep CO band absorption, thus putting the FUor classification of this source by Strom & Strom (1993) in doubt.

Our deep interference filter images reveal several HH objects in the region. Such objects are distinguished by their pure emission line spectra with strong emission in H α and the [SII] 6717/6731 doublet, as well as their characteristic knotty structure. A compact group of previously discovered HH knots, HH 65, is located about 3 arcmin northwest of the source (Reipurth & Graham 1988). It is unclear if this object is related to HBC 494, since it is located towards the red lobe of the molecular outflow associated with Re 50, and should thus be fairly deeply embedded. Moreover, a major molecular hydrogen flow has been found northwest of Re50 by Stanke et al. (2002). Two new groups of HH objects are found in our images, here named HH 1121 and 1122, see Figure 5. HH 1121 consists of two knots, the western knot is the brighter one, and located at α_{2000} 05 40 21.3, δ_{2000} -07 29 33. HH 1122 forms a knot complex just north of Re50 including some knots projected onto Re50 itself; it was previously detected in near-infrared H $_2$ emission as MHO 161 (Stanke et al. 2002, Davis et al. 2009, 2010). The brightest knot of HH 1122 is located at α_{2000} 05 40 29.3, δ_{2000} -07 28 41. Two faint H α knots are seen just west of Re50N, they are part of a larger diffuse H α cloud, whose nature is unclear. Re50N itself is slightly brighter in H α than in the closeby continuum, suggesting that the illuminating source may have the H α line in emission. No emission jet could be discerned along the main axis of Re50N.

4. DISCUSSION

The principal question that emerges from the data presented here is, what is the origin of the

dramatic brightening of Re50N? The two obvious possibilities are either that the source has undergone a FUor eruption, or that obscuring material has caused shadows to play on the surrounding molecular cloud surface. Sometime between 1955 and 1979 the Re50 and Re50N nebulae appeared (Reipurth & Bally 1986), and this was ascribed by Strom & Strom (1986) to a FUor event in the source based on its P Cygni profile at $H\alpha$, which they were able to observe using the reflection nebula as a scattering surface towards the optically invisible star. Such a FUor event would be able to form a prominent reflection nebula; a fine example is V1057 Cygni, which upon its FUor outburst in 1969 formed a large reflection nebula that expanded as the light from the stellar brightening traveled across the surrounding cloud (Duncan et al. 1981).

There are several reasons why the FUor interpretation may not hold in this case. First, the near-infrared spectrum in Figure 4 shows a smooth red continuum, in contrast to the deep CO bandhead absorption characteristic of FUors. This is apparently not a temporary spectral appearance, since Reipurth & Aspin (1997) saw a similar appearance in a lower dispersion spectrum obtained in 1996. Second, while it is true that the $H\alpha$ profile presented by Strom & Strom (1986) displays the profound P Cygni profile characteristic of FUors, such profiles are sometimes seen in active T Tauri stars, e.g., AS 353A and V1331 Cyg (Reipurth et al. 1996, Petrov et al. 2014). Third, if the brightening prior to 1979 was due to a FUor outburst, then the present brightening should be a second FUor outburst subsequent to or on top of the previous eruption. Such sequential outbursts are not commonly known in other FUors, in fact only the FUor V1647 Ori has been known to have had two outbursts (Aspin et al. 2006).

For the above reasons, we suggest that the brightening reported here has a more straightforward explanation. Reflection nebulae around young stars are often variable, e.g. the cases of R Mon (Hubble 1916), R CrA (Knox-Shaw 1916), PV Cep (Cohen et al. 1981), and L483 IRS (Connelley et al. 2009). This is ascribed to dusty and clumpy material orbiting the young stars, causing a play of shadows on a nearby cloud surface (e.g., Graham & Phillips 1987). Although the appearance of the Re50 region is only sporadically doc-

umented, a fortuitous image taken in 1986 shows Re50N with almost the same brightness and appearance as today (Reipurth & Madsen 1989). In contrast, Re50 itself used to be a very bright nebula, but it has now faded greatly to the point of almost disappearing. Comparison of Figure 1 with the abovementioned earlier images suggest that the fading started to the west and moved eastwards, as if a curtain of obscuring material was drawn somewhere along the line of sight to the illuminating source. These changes occur on longer time scales than usually seen in reflection nebulae around young stars. This, combined with the complete absence of any reflection nebula on early photographic images of the region, suggests that, rather than resulting from clumpy material orbiting the star, we may be witnessing the first light escaping from the embedded source as its outflow cavity begins to break through the surrounding cloud material (Reipurth & Bally 1986). Even very slow movement of such obscuring material can have a significant effect at a distance if it occurs near the star.

While we favor the shadow play explanation over the FUor hypothesis, it does not mean that the illuminating source is not heavily accreting. The strong veiling that is seen in the near-infrared spectrum is very rare; among the 110 Class I protostars studied spectroscopically by Connelley & Greene (2010), only two have spectra with similarly strong veiling. In their study, $\sim 85\%$ of the sources show spectral features indicative of accretion, with correlations between veiling, CO emission, and $Br\gamma$ emission. It is notable that HBC 494 does not show any CO bandhead emission nor $Br\gamma$ emission, suggesting an abundance of hot dust but little or no emitting gas. Additionally, the bolometric luminosity of the source, estimated at $\sim 250 L_{\odot}$, is much higher than typical low-mass young stars, and makes the source one of the most luminous in the L1641 cloud. Gramajo et al. (2014) have modelled the energy distribution of the driving source, and find a substantial disk accretion rate of $\sim 1.3 \times 10^{-6} M_{\odot} \text{yr}^{-1}$. The Re50 protostar is evidently in a very active accreting state.

We are grateful to Nancy Levenson for allocating Director's Discretionary Time at Gemini-South for this study (GS-2014A-DD-1), and to

the Gemini-South staff for carrying out the observations. The Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina). We thank Megan Ansdell and Heather Kaluna for obtaining early verification images at the UH 2.2m telescope. This material is based upon work supported by the National Aeronautics and Space Administration through the NASA Astrobiology Institute under Cooperative Agreement No. NNA09DA77A issued through the Office of Space Science. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and of NASA's Astrophysics Data System Bibliographic Services.

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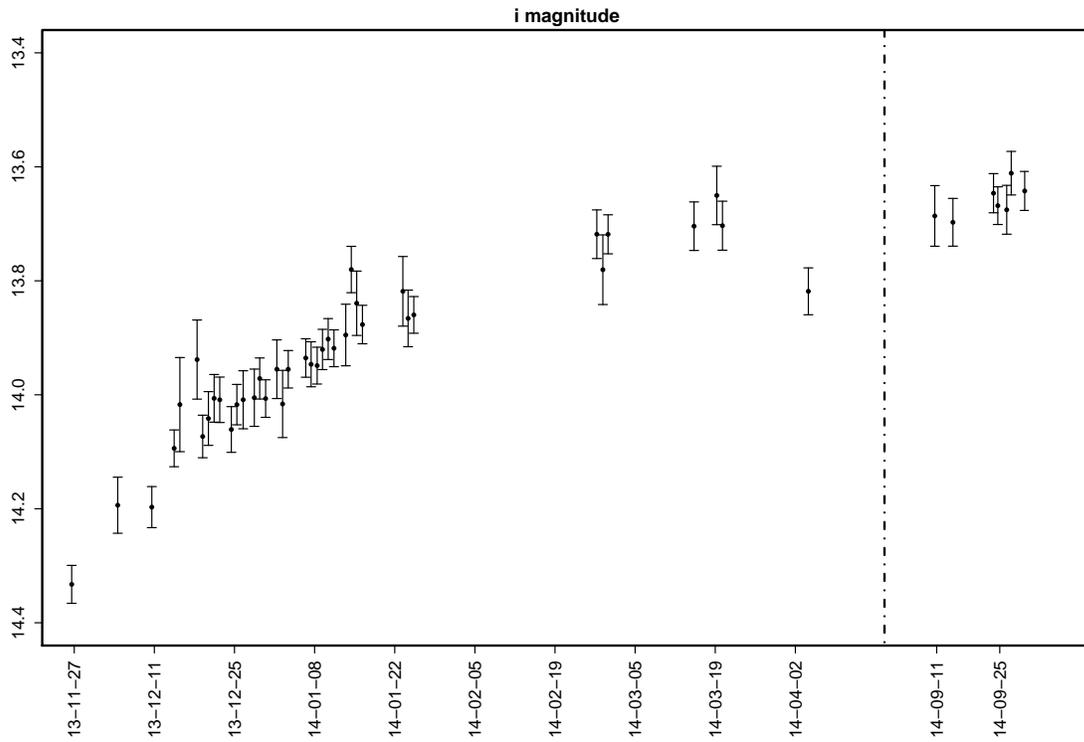


Fig. 1.— A light curve of Re50N obtained in a Sloan i -filter with the VYSOS 20-inch robotic telescope. A 17.8 arcsec aperture was used to extract the photometry.

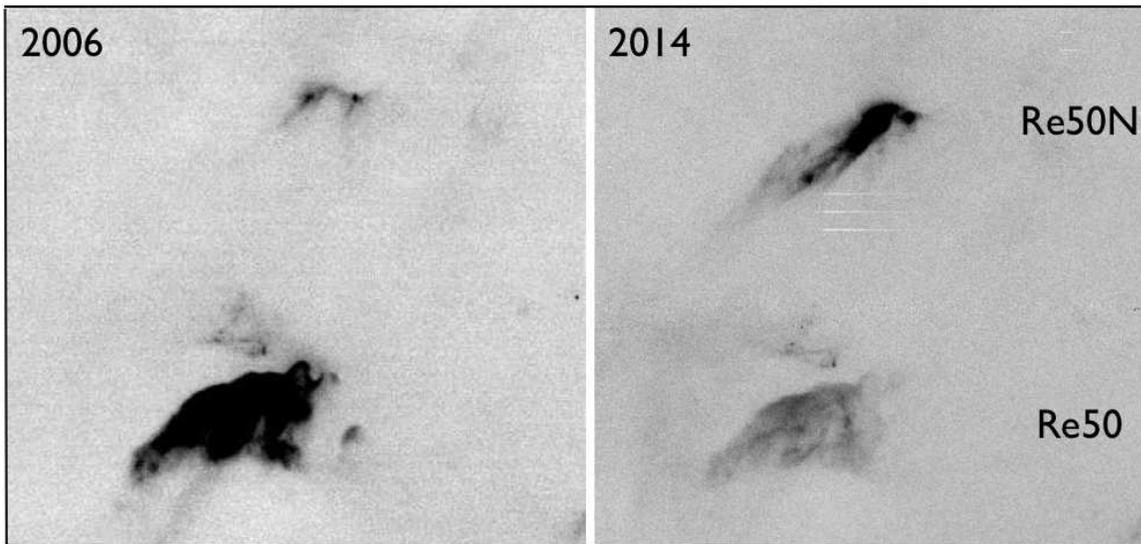


Fig. 2.— The region of Re50 and Re50N observed in 2006 with SuprimeCam at the Subaru telescope, and in 2014 with GMOS at the Gemini-S telescope. A [SII] filter was used for both images. The seeing was in both cases 0.6 arcsec. Each image is about 3 arcmin wide. North is up and east is left.



Fig. 3.— A color mosaic of Re50N based on J,H,K images obtained at the IRTF (J is blue, H, is green, and K is red). The source HBC 494 is the red object, it is detected only in the K-filter. The image is about $35''$ wide, with north up and east left.

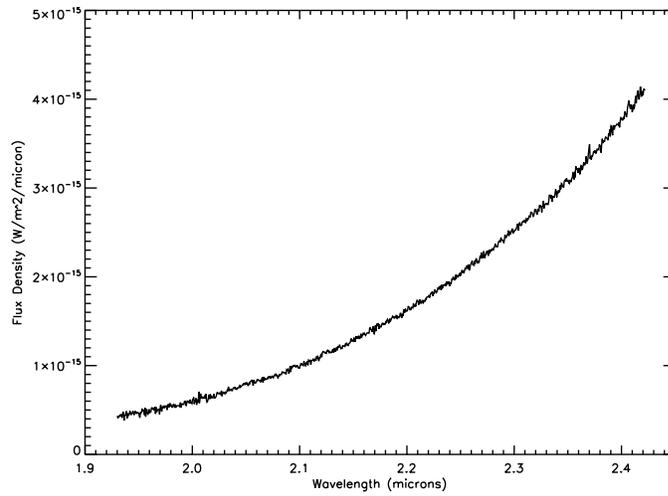


Fig. 4.— A near-infrared spectrum between 1.9 and $2.4 \mu\text{m}$ of the source HBC 494 obtained with SpeX at the IRTF.

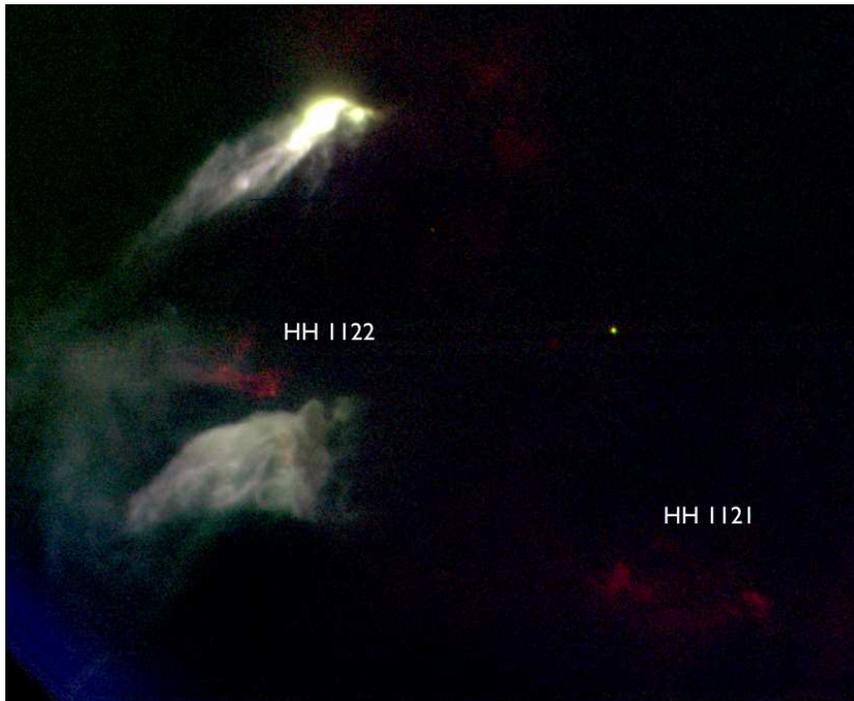


Fig. 5.— Herbig-Haro objects are located around Re50 as seen in this color figure where blue is r , green is i , and red is the sum of $z + H\alpha + [SII]$ images, all from Gemini-S. The new HH objects HH 1121 and 1122 are seen as faint red features emitting in $H\alpha$ and $[SII]$. The figure is a little more than 3 arcmin wide. North is up and east is left.