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The "Criss-Cross Nebula": an interaction of the Orion-Eridanus Bubble with a small interstellar cloud

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Abstract. A new, small ($6' \times 3'$) filamentary emission nebula of very low surface brightness ($\ell = 197\overset{\circ}{.}0, b = -37\overset{\circ}{.}8$) is found to be projected towards the center of a huge expanding (40 km s^{-1}) H I shell (Brown et al. 1995) surrounding the Orion-Eridanus Bubble. Moderate quality spectra taken by us show low-excitation species but allow us to estimate the electron density ($\simeq 10^2$ cm^{-3}). The spectra point to an excitation by a shock of low velocity ($\simeq$40 km s^{-1}). No dust emission (IRAS) is seen at the position of our object, which could well be an outlying clump of material associated with the L1569 dust cloud at a distance of about 130 ± 20 pc, and which appears to be at the front side of the Bubble. We believe that our "Criss-Cross Nebula", dubbed so due to its specific morphology, might represent a very small interstellar dust cloud that is just in the process of destruction by the blast wave of a supernova that gave rise to the Orion-Eridanus Bubble and to some of its characteristics like the Eridanus soft X-ray enhancement. Known examples of clouds overrun by blast waves are exceedingly rare and a more detailed study of this new nebula is therefore highly recommended.

Key words: ISM: supernova remnants – ISM: bubbles – ISM: individual: Orion-Eridanus Bubble

1. Introduction

Energy from Orion OB 1 is reported to be responsible, in a direct and/or indirect way, for one of the apparently largest structures of the galactic sky, the Orion-Eridanus Bubble (OEB) and the associated Eridanus soft X-ray enhancement (EXE). The bubble is located close to the Sun and its size is comparable to its distance.

One of the first extensive analyses of this object was carried out by Reynolds & Ogden (1979) who studied faint Hα emission in this region. They detected line splitting in Hα and [N II] consistent with emission by an expanding shell and concluded that a large cavity extends from the Ori OB 1 association well into Eridanus. They suggested that the cavity, which they found to have an angular size of $47° \times 33°$ was produced by stellar winds and/or supernova explosions originating in the Ori OB 1 association.

In a multiwavelength study of the EXE enhancement, Burrows et al. (1993) suggested that the enhancement consists of two distinct components, namely a large hook-shaped one and a small circular one at different temperatures. Whereas the latter could be a stellar wind bubble, they proposed that the former is a nearby superbubble blown by the winds of the Ori OB 1 association and possibly reheated by supernovae.

Brown et al. (1995) examined the cavity filled with hot ionized gas and the surrounding bubble with the aid of data from the Leiden/Dwingeloo H I survey and presented neutral-hydrogen maps which allowed the identification of the H I filaments and arcs delineating the bubble and the derivation of its expansion velocity. They gave $\ell \approx 195°, b \approx -35°$ for the center of the OEB.

ROSAT observations of the EXE were used by Snowden et al. (1995) and Guo et al. (1995). Both groups of authors show that the entire enhancement spans a total of $\approx 35°$ in galactic latitude and $\approx 20°$ in galactic longitude, centered at $\ell \approx 200°, b \approx -32°$. It appears that the smaller of the X-ray components cited by Burrows et al. (1993) is not an isolated bubble but is linked to a more extensive soft X-ray enhancement that probably originates in a galactic halo. By observing selected regions in the EXE Guo et al. (1995) found that in the direction of $(\ell, b) \approx (200°, -47°)$ their best estimate of the distance to the near side of the OEB is 159 ± 16 pc and estimated the center of the bubble in this direction to be about 226 pc away. They found a density and thermal pressure for the EXE of 0.015 cm^{-3} and 4.9 10^4 K, respectively.

It is obvious that foreground material, clouds at the borders (like the molecular cloud L1569) and inside the OEB are responsible for the high complexity in this region of the sky. Evidence for a direct interaction of the bubble with any of the clouds are scarce.

Investigation of an interaction of a supernova remnant (SNR) with an isolated cloud have been carried out by Fesen

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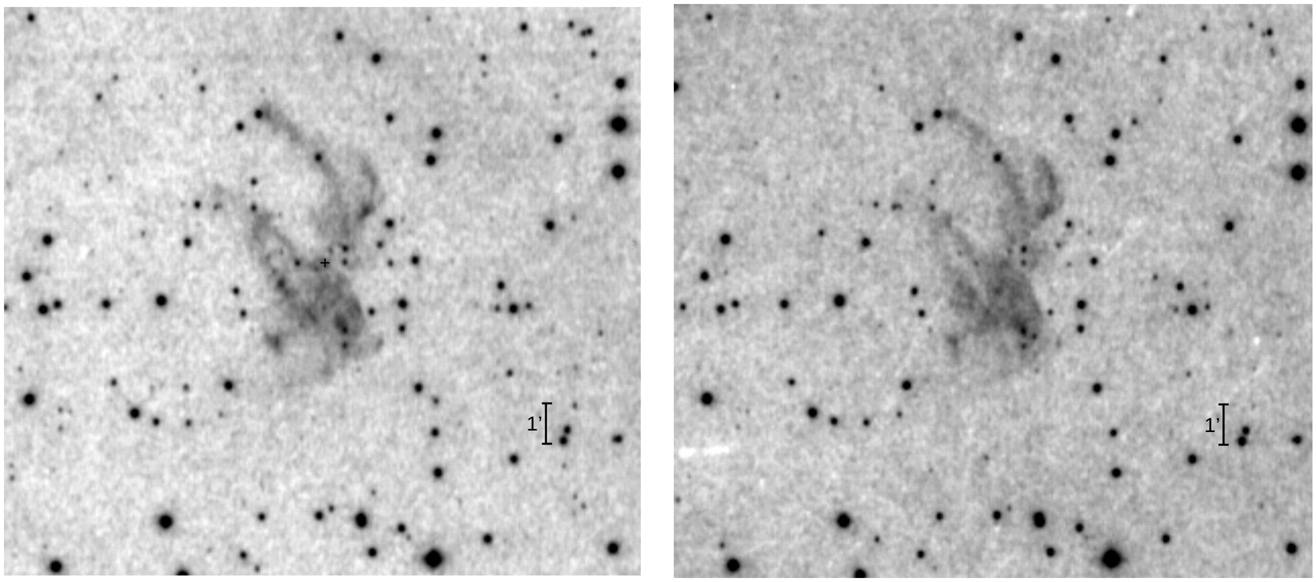

Fig. 1. The Criss-Cross Nebula, reproduced from the Palomar Observatory Sky Survey (POSS) red-sensitive print (left) and blue-sensitive print (right). The coordinates given in the text refer to the plus-sign. North is up and east is left.

et al. (1992), Klein et al. (1994) and Graham et al. (1995). The former two groups of authors presented investigations of an apparently isolated shocked cloud in the east of the Cygnus Loop that they consider to be a convincing case of an interaction of a blast wave with an interstellar cloud. Graham et al. (1995), however, suggest that this object is not a small cloud that has been overrun by the blast wave, but the tip of a larger cloud.

It therefore appears that up to now there is no single unambiguous well-studied practical case for the interaction of a shock wave with an isolated interstellar cloud. The "Criss-Cross Nebula", detected by us long ago during systematic searches on the Palomar Sky Survey but never published, was found to be projected against the very center of the huge Orion-Eridanus H I shell which is shown in Fig. 8 of Brown et al. (1995). Its location, the curious filamentary morphology and the nature as an emission nebula explainable as due to a mild shock, led us to carry out a preliminary investigation of this object, which might represent the results of such an interaction.

2. Observations

Spectroscopic observations of the Criss-Cross Nebula (CCN) were obtained in two different runs at the 1.82m telescope of the Asiago Observatory with the Boller & Chivens spectrograph equipped with the 300 lines mm^{-1} grating and a UV-coated TH 7882 CCD. The slit width was 250 μm. The first observation was carried out on 1995 September 3 in the range 4710–6910 Å: two exposures of 30 min each were taken, one from the center, and the other from the south of the object. Another spectrogram was kindly secured for us by A. Bianchini on 1995 November 15 with the same configuration of the telescope but covering the spectral range 4150–6150 Å, having an exposure time of 1 hour.

The resolutions of the spectra are $\sim$ 10 Å. At least one standard star from the lists of Oke & Gunn (1983), Hamuy et al. (1992), and Baldwin & Stone (1984) was observed on each night. The spectra were reduced with the IRAF package, employing overscan subtraction, flat fielding, and wavelength and flux calibration.

The relative intensity of the lines of the three spectra was similar and we added them to improve the signal to noise ratio. The resolution was sufficient to separate Hα from the [N II] lines. The red part of the composite spectrum is shown in Fig. 2.

In 1996 February 7 B. Duffee kindly obtained for us two narrow-band images (Hα+[N II]) with the 60cm HSH Telescope operating at the University of Toronto Southern Observatory equipped with a blue-coated PM512 CCD, that had a field of $4' \times 4'$. Both the images show the central part of the nebula. The images were corrected for bias, flat field and cosmic rays incidents by use of the IRAF package and were added, but do not contain any noticeable additional information compared to the reproduction of the red-sensitive POSS exposure (which acts like a broad-band Hα+[N II] filter). Consequently, these images are not shown here.

3. Results and discussion

The Criss-Cross Nebula, named thus because of its peculiar intersecting filaments (see Fig. 1) has not been noticed before. According to the Simbad database, no object is listed within $10'$ around the center of the nebula (1950; α = $04^{\rm h}07^{\rm m}39\overset{\rm s}{.}7$, δ = $-05°06'25''$; ℓ = $197\overset{\circ}{.}00$, b = $-37\overset{\circ}{.}83$). Because of its similar surface brightness on the red-sensitive and blue-sensitive prints it was originally not clear whether we are dealing with a reflection or an emission nebula.

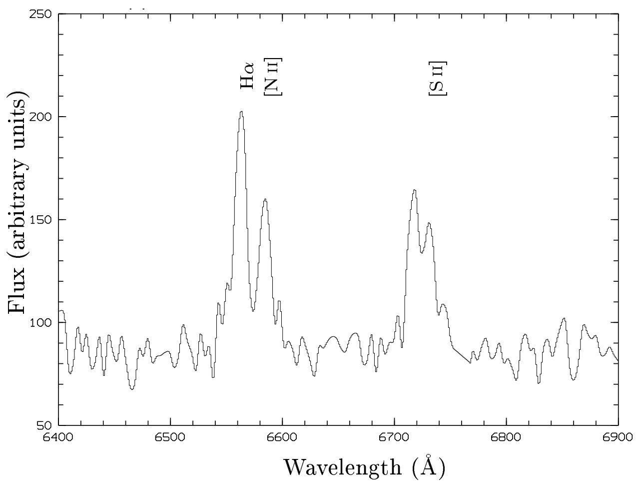

Fig. 2. The red part of the spectrum of the Criss-Cross Nebula. It actually consists of an addition of two (quite similar) spectra, one across the center of the object (E – W), the other $1'$ to the south. The blue part (not presented here) is rather noisy and shows nothing but the faint Hβ line.

Table 1. Relative line fluxes of the Criss-Cross Nebula

Ident	λ(Å)	F
Hβ	4861	100:
[N II]	6548	72
Hα	6563	344
[N II]	6583	217
[S II]	6717	221
[S II]	6731	173

3.1. The spectrum

The spectra presented here (Fig. 2) prove that this object is an emission nebula. In Table 1 we present the measured relative fluxes of the lines; we estimate that the errors associated are of the order of 5%, but for Hβ that lies in a noisy part of the spectrum we estimate $\pm 20 - 30\%$. The Hα/Hβ ratio appears to be about 3. Interestingly, there is no trace of [O III]λ5007 Å; this fact is not a consequence of any noticeable interstellar extinction (note the high galactic latitude, the Hα/Hβ ratio, and the lack of an IRAS counterpart - see below).

Unfortunately, our spectrum does not extend to the [O II]λ 3726/29 Å region, but we believe that CCN strongly emits in this line-pair due to its brightness on the blue-sensitive POSS print the bandpass of which has an effective wavelength of about λ 4100 Å and extends from about 3500 to 5000 Å; in principle, there is no other line in the blue prominent enough to be responsible for the emission on POSS blue. On the red side of our spectrum, we notice rather strong sulphur lines. The ratio of these lines, [S II]$\lambda\lambda$6717,6731 Å gives an estimate of electron density of $n_{\rm e} \sim 114$ cm^{-3} (Osterbrock 1989), with a nominal error of the order of about 10%.

3.2. Photoionization or shock?

Both the lack of a blue central star, the lack of any IRAS emission at the position of the nebula and its peculiar, filamentary morphology exclude that we are dealing with a planetary nebula or an H II region. A nova shell can be ruled out as the angular size of the nebula would then imply a very close distance given the small ejected masses (ca. $10^{-4} M_\odot$) during a nova explosion, which would lead to a quite bright central star. A wind-driven nebula around a luminous, massive star can be ruled out, of course. Is the nebula a Herbig–Haro object? The dust-free (or dust-poor) surroundings speak against that assumption. A useful tool to establish the nature of an emission nebula is the Hα/[N II] versus Hα/[S II] diagnostic diagram (García Lario et al. 1991) that separates the objects with respect to the ionization mechanism (photoionization or shock), and also differentiates supernova remnants (SNR) from Herbig–Haro objects. The line ratios of the CCN (Hα/[N II]=1.2 and Hα/[S II]=0.9) put it in the SNR zone.

Is CCN a supernova remnant? At least not in the usual sense, since there is no radio source known there and the object does not show up in the ROSAT maps.

The relative intensity of the lines in the spectrum of the nebula indeed indicates the presence of a shock. One of the quantitative criteria used to identify SNR with respect to other emission line nebulae is a strong [S II]$\lambda\lambda$6717,6731 Å emission (Fesen at al. 1985). The CCN Hα/[S II] ratio is ~ 0.9 and supports such an interpretation.

Another interesting characteristic is the non-detection of the line [O III]λ5007 Å. This enables us to give a first approximate upper limit for the shock velocity of 60 km s^{-1} (Fesen at al. 1992).

We then tried to apply the models of radiative shocks calculated by Hartigan et al. (1994). They calculated the emission-line ratios from a series of shocks that cover different shock velocities, preshock densities and magnetic fields. The estimation of the magnetic field is not possible for us and we therefore assume that we deal with the average magnetic field of the ISM.

By using the diagrams presented in Hartigan et al. (1994) we evaluated the shock velocity ($v_{\rm s}$) from the [S II]/Hα ratio which is almost independent of the magnetic field; for the measured value of 1.1 we found $v_{\rm s} \sim 40$ km s^{-1}. In principle, we could also estimate $v_{\rm s}$ from the Balmer decrement (Hα/Hβ=3.4 gives $v_{\rm s} \sim 60$ km s^{-1}), but we find it more reliable to rely on the lower of the two values, which also agrees with the lack of the [O III]λ5007 Å line.

3.3. The location of the nebula

The Criss-Cross Nebula is projected against the very center of the Orion-Eridanus H I shell which is shown in Fig. 8 of Brown et al. (1995). These authors found a velocity of the outer borders of the shell of about 40 km s^{-1}, i.e. the same velocity as we inferred from the shock models. These facts combined with the possibility that the OEB might be due to a supernova from a runaway OB star originally associated with Orion OB1 (Brown

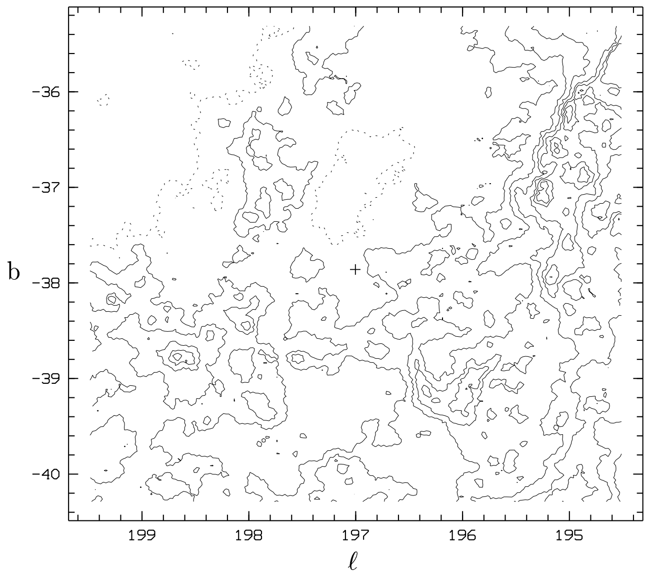

Fig. 3. A contour plot of the IRAS 100 μm emission corrected as described in the text. The field is 5° wide and the position of the Criss-Cross Nebula is marked with a plus-sign. The contours are from 6 to 11 in steps of 1 unit; a contour at 4.8 is marked with a dotted line. The emission at $\ell < 197°$ obviously stems from outlying portions of the dark cloud L1659

et al. 1995) and the morphology and spectrum of CCN suggest that there might be an intimate connection between the CCN and the Orion-Eridanus Bubble.

It is obvious that the foreground material and the clouds, at the borders and inside the OEB, are responsible for the high complexity seen in the X-ray maps of this region (Guo et al. 1995; Snowden et al. 1995). A particularly striking shadow-like feature in X-rays is caused by the dark cloud L1569 (= MBM 18; centered at $\ell \approx 189°$, $b \approx -36°$) the distance of which has been determined to be 130 ± 20 pc by Franco (1988). Interestingly, Penprase et al. (1990) in their optical spectroscopy of this dark cloud found observed velocity differences $v(\mathrm{CH}^+) - v(\mathrm{CH})$ and $N(\mathrm{Ca\,II})/N(\mathrm{Na\,I})$ to be consistent with shock excitation. We suggest that these effects are due to the interaction of the OEB with L1569, since the distance of the near side of the OEB (159 ± 16 pc at $(\ell, b) \approx (200°, -47°)$) is in accordance with such an assumption.

Based on the IRAS 100μm map of the region around CCN and its location in the X-ray maps of Snowden et al. (1995), it is suggested that the nebula is located at the near side of the OEB and is an outlying cloudlet of the L1569 cloud. In the discussion of absorption features the latter authors also presented an IRAS 100μm map, corrected for the oversubtraction that could be found in the IRAS Sky Survey Atlas (ISSA). We decided to redo the same steps as they did to construct the map, to obtain a map (Fig. 3) with much more details and with a smaller field in order to clearly see where CCN is located. The process consists in the normalization of the 100μm map to the H I data from Stark et al. (1992) using the "typical" high-latitude 100μm/N_H ratio of 0.85 10^{-20} cm^2 MJy sr^{-1} (Boulanger & Pérrault 1988). In the corrected IRAS map of Fig. 3 the CCN lies in the center (plus-sign); an inspection of Fig. 1 of Penprase et al. (1990) reveals that the 100μm emission at $\ell \lesssim 197°$ appears to be the outlying southern portions of L1569. A closer look at the 100μm map in Fig. 3 (note that our nebula has a size of a few arcmin only) shows that the CCN lies close to the tip of a kind of dusty protrusion, but appears to be isolated from it.

An examination of the X-rays maps of Snowden et al. (1995) shows, that the location of the CCN in the 1/4 keV band (which is more sensitive to absorption than the 3/4 keV band) is quite close to a very sharp straight border, but just a bit away from the intense emission, i.e. in the shadowed part. Would our object be on the distant part of the OEB, then - taking into account the position of it in Fig. 3, we could rather expect intense X-ray emission in front of it.

Anyway, it seems plausible that the CCN is (was) connected with the L1569 cloud and its distance consequently is of the order of 150 pc.

3.4. The CCN: a cloud overrun by a blast wave

The picture that emerges is as follows: The Criss-Cross Nebula appears to be an isolated object at the near side of the OEB. It has probably been subject to a process that has destroyed the dust in it, leading to a filamentary morphology and to emission line ratios that are consistent with those seen in supernova remnants.

Could the CCN be the result of an interaction of a small interstellar cloud with a shock front? In order to investigate this hypothesis we have tried to estimate the dimensions and the mass of the nebula. We again use the Hartigan et al. (1994) shock models and derive the ionization fraction, defined as the ratio between the electron and the total density. This results in a value of 9%, so we cannot assume that our nebula is fully ionized. Next, we estimate an approximate value of the total density to compute the mass. We assume that the nebula lies at a distance of 150 pc, has a cylinderical shape (angular dimension $6' \times 3'$, linear dimension 0.26×0.13 pc), a filling factor of 0.1 and that its gas has cosmic abundances with a molecular weight ~ 1.24. Thus we find a mass of $\approx 0.01 M_\odot$. From the shock models we derived also the compression factor (=27) and consequently the preshock density of 47 cm^{-3}; by assuming an originally spherical nebula with a filling factor of 1 we estimate an initial radius of ≈ 0.13 pc - a small nebula indeed.

In a theoretical investigation of such a process, Klein et al. (1994) found that a striking aspect of the interaction of a shock wave with a cloud is the development of powerful vortex rings, which play an important role in the destruction of the cloud. Before the destruction, a flattened core with some arm-like features will develop. Particularly illustrative is also the three-dimensional model of such an interaction as investigated by Stone & Norman (1992): their Fig. 1 shows how the cloud is distorted and has produced warped arms or filaments, where the ratio of dimension of the distorted cloud to the original undisturbed one is ~ 2. This representation has a strong resemblance with the morphology of CCN. Since CCN is, however, projected against the center of the OEB and appears to be located at the front side, we see the effect of such an interaction from the rear.

3.5. The OEB - created by a supernova?

There is no clear unanimous opinion on the origin and present conditions of the Orion-Eridanus Bubble, but the Orion OB1 association is suspected of playing a key role by emitting ionizing photons, providing a stellar wind, and perhaps by having ejected a runaway star that has exploded as a supernova. If our interpretation of the CCN is correct, then the belief that the OEB is a result of a supernova explosion has gained considerable support. We checked lists of pulsars but found no suitable candidate as a counterpart: the closest one is PSR J0421−0345 (Manchester et al. 1996) $\sim 3^\circ$ away from the CCN, but it is not in the direction Orion OB 1 - CCN. A search for a pulsar beyond the direction Orion OB 1 - CCN (particularly Ori OB 1a - see van Rensbergen et al. (1996)) might pay off.

4. Conclusion

We have discovered a very faint small filamentary emission nebula (the "Criss-Cross Nebula"), projected onto the center of the huge Orion-Eridanus Bubble. The nebula can best be explained as a SNR(-like) object and shows spectroscopic signs of a slow (ca. 40 km/sec) shock. This value is in accordance with the expansion velocity of the OE H I shell. It appears that CCN lies at the front side of the Bubble and is an outlying, but isolated part of the L1569 dark cloud, in a distance of about 150 pc. The object has no counterpart at 100μm.

We believe that the Criss-Cross Nebula is the result of an interaction of a shock wave with a cloudlet. The shock wave could have been created by a runaway star from the Orion OB 1 association, and which could have also led to the Orion-Eridanus Bubble. The present appearance of the nebula is perhaps the result of it being viewed from the rear side, and in the process of destruction. Because of the rarity of examples of such interactions, CCN is of considerable interest. Much more detailed investigations of this nebula are urged to carry out. Also, efforts should be undertaken to discover additional Criss-Cross Nebulae.

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