The Horsehead nebula: a beautiful case

The Horsehead nebula has been a great source of speculation and inspiration for the last century. We give a brief discussion of why that is as well as summarizing our recent observations using SOFI on the NTT.

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A thing of beauty is a joy for ever it has been said and the Horsehead Nebula is a case in point. Poems have been written about it (see one of them by Lisa Odland, Figure 1) and its mysterious shape has clearly been an attraction for many. It has also been a puzzle for many astronomers ever since Herschel and those who followed him turned their attention to the nature of the nebulae. The characteristics of these objects became much clearer after it was possible to take photographs and in fact the discovery of the Horsehead can be said to go back to the 1880s when the photographic programmes in Harvard and elsewhere got started. It was based on this information that E. E. Barnard, J. C. Duncan and others exploited the new telescopes of the 20th century (mainly Mt. Wilson and Yerkes) and started really to understand the nature of the mysterious dark nebulae.

This was of fundamental importance for a number of reasons. Above all, the nature of the obscuring particles was critical for understanding the distance scale and the nature of our Milky Way. That was presumably one reason why Hubble was interested in the nature of the particles causing reflection nebulae. But another reason was to understand the nature of these clouds. Where did they come from and where were they going? And why were they partially in emission and partially dark? And were the dark areas due to holes or rifts in the nebulosity?

Barnard was already convinced in 1913 that the Horsehead (not then known as such) was due to a dark object projected against bright nebulosity (see Figure 1). He also noted that the west side is very well defined and sharp! We know now that this sharpness is due to the fact that the Horsehead is being irradiated by the UV radiation of the O9 star σ Ori half a degree (3.5 parsec) away to the west. Figure 2 shows a modern map of the CO emission which illustrates the situation. The Horsehead is clearly visible as part of the L 1630 molecular cloud. The UV radiation at wavelengths below 912 Å (the hydrogen ionization edge) ionizes and ablates the western edge gas and is thus slowly destroying the cloud. However, in the meantime, the edge lights up both due to the hot ionized gas streaming away and due to the dense neutral gas on the eastern side of the ionization front. This latter layer is compressed due to the effect of the ionization front and heated by UV radiation at wavelengths longward of 912 Å. This has the consequence that the neutral dense layers also emit strongly and thus the Horsehead, in addition to all its other properties, is a fascinating laboratory with which to study the physics of ionization fronts. In fact the edge of the Horsehead is an example of what has come to be known as a PDR or Photon Dominated Region where incident UV radiation from a hot star heats a dense neutral gas layer. Several teams around the world including the Meudon group led by Jacques Le Bourlot and Evelyne Roueff have developed sophisticated models of the structure of such dense neutral layers and part of our interest in the Horsehead has been to test such models. The edge of the Horsehead – a PDR viewed almost edge-on – allows us to follow *directly* the penetration of the far-UV radiation into the cloud.

Ah, to softly slip behind the scene,
One clear and snow-draped, silent winter night,
To pierce the density which seems to screen,
Obstruct the splendour of that cosmic light,
To pass beyond that dark and mystic cloud,
Which looms like portal in a garden wall,
The ancient loveliness within to shroud,
How it ones fancy does inspire, enthrall,
In that great starlit garden of the sky,
Where light eternal dwells in calm repose,
Who knows what beauty there might greet the eye,
What undreamed truth a brief glimpse there disclose,
As strange as thought, to thought there is no space,
At will, ones thoughts the universe may embrace.

Figure 1: The Horsehead is clearly visible in the plate from Barnard's 1913 article shown on the left. This or something like it was the inspiration for Lisa Odland's poem.

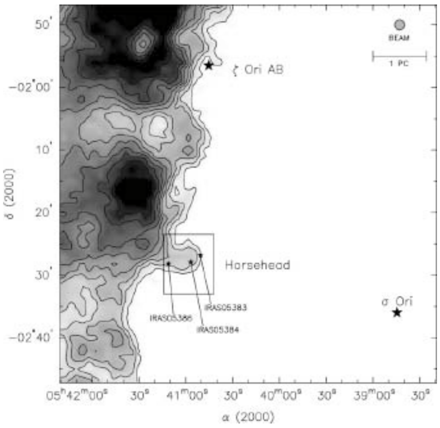

Figure 2: The exciting σ Ori O9 star is shown here on a large CO (1-0) integrated intensity of part of the L 1630 molecular cloud made with the Bell Labs 7-m telescope. The Horsehead is seen as an emission region extended out to the west. Note the presence of a young protostar IRAS 05383 embedded in the Horses crest.

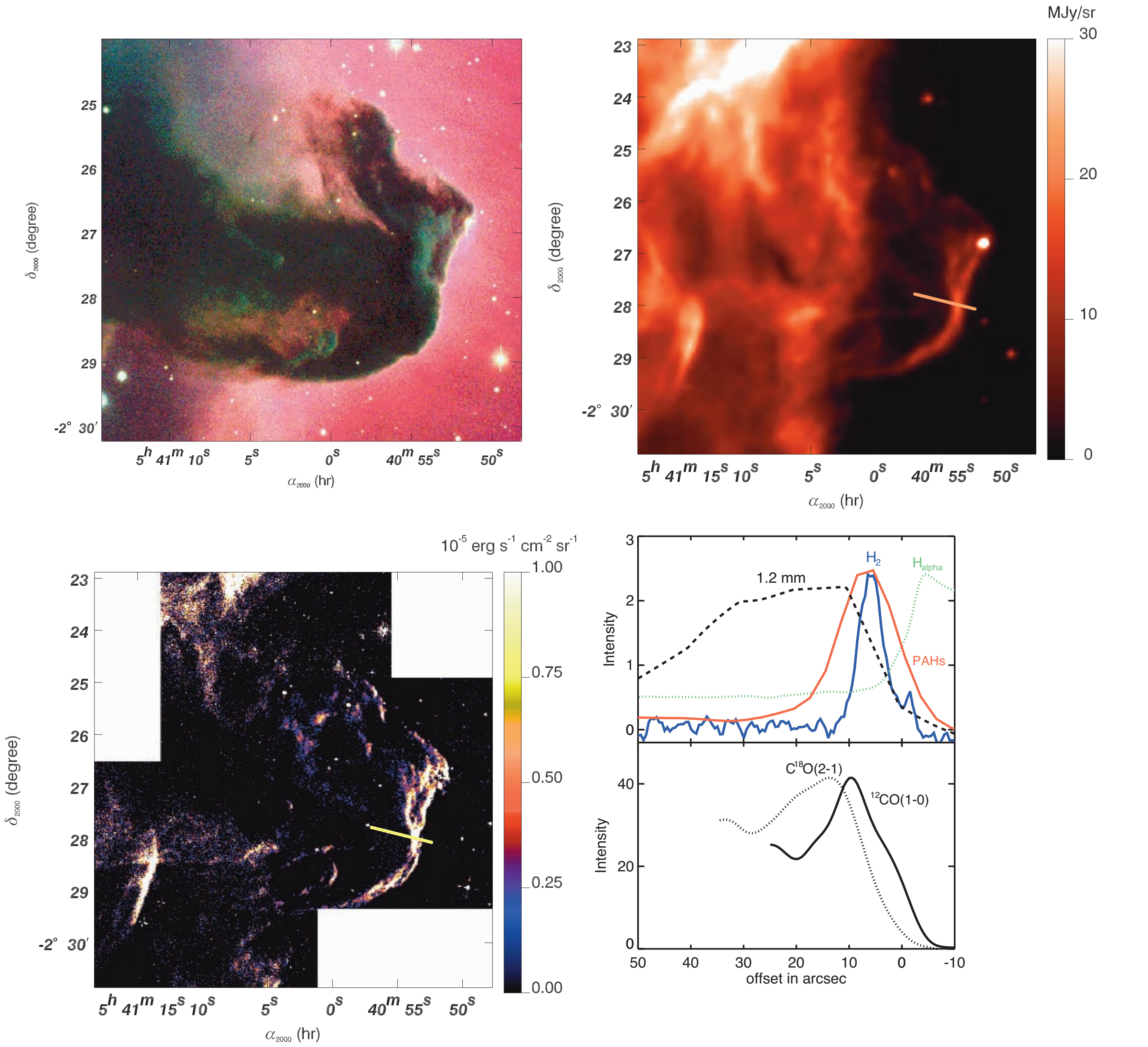

Figure 3: **Top left:** VLT composite (B,V and R bands) image. **Top right:** ISOCAM (6″) image (5–8.5 µm). **Bottom left:** SOFI/NTT (1″) image in the H_2 2.12 µm line. **Bottom right:** Emission profiles throughout the edge of the Horsehead nebula along the cut shown in the maps.

Why you may ask does this matter apart from the intellectual satisfaction of understanding ionization fronts and PDRs? One reason is the evidence for star formation associated with such compressed layers. In particular, there appear to be young protostars associated with the Horsehead. In the early 1980s, Reipurth and Bouchet used the ESO 3.6-m and the Danish 1.5-m to get deep images of the Horsehead in a number of filters as well as infrared photometry for a number of interesting objects. One of these (B33-1) was later detected by the IRAS satellite (IRAS05383, see Figure 2) at wavelengths beyond 10 microns and seems likely to be very young and associated with an outflow. It is situated interestingly right on the crest of the Horsehead!

High angular resolution images of the H_2 emission

Our involvement in this began when, in order to study the physical structure of the Horsehead nebula PDR, we obtained high angular resolution imaging observations of the H_2 1-0 S(1) line emission at 2.12 µm using SOFI on the ESO NTT telescope. This line emission is very sensitive to both the FUV radiation field and the gas density and the angular resolution (~ 1″) is ~ 5–10 times better than previous observations at infrared and mm wavelengths. We were also motivated by the image obtained with ISOCAM on the ISO satellite showing emission in the so-called UIR or Unidentified Infrared Bands at 6.2 and 7.7 µm (see Figure 3) usually associated with PAH molecules or Polycyclic Aromatic Hydrocarbons. The edge of the Horsehead nebula represents one of the sharpest mid-IR filaments (width: 10″ or 0.02 pc) detected in our Galaxy by ISOCAM (Abergel et al. 2003).

Sharp gas density gradient

The H_2 fluorescent emission presents striking filaments which coincide with those seen with ISOCAM. What does this mean? In addition to the front where hydrogen gets ionized (see the H_α line emission shown in red in the VLT composite image, Figure 3), the models predict a front somewhat further into the cloud where H_2 gets dissociated and our observations appear to delineate this layer.

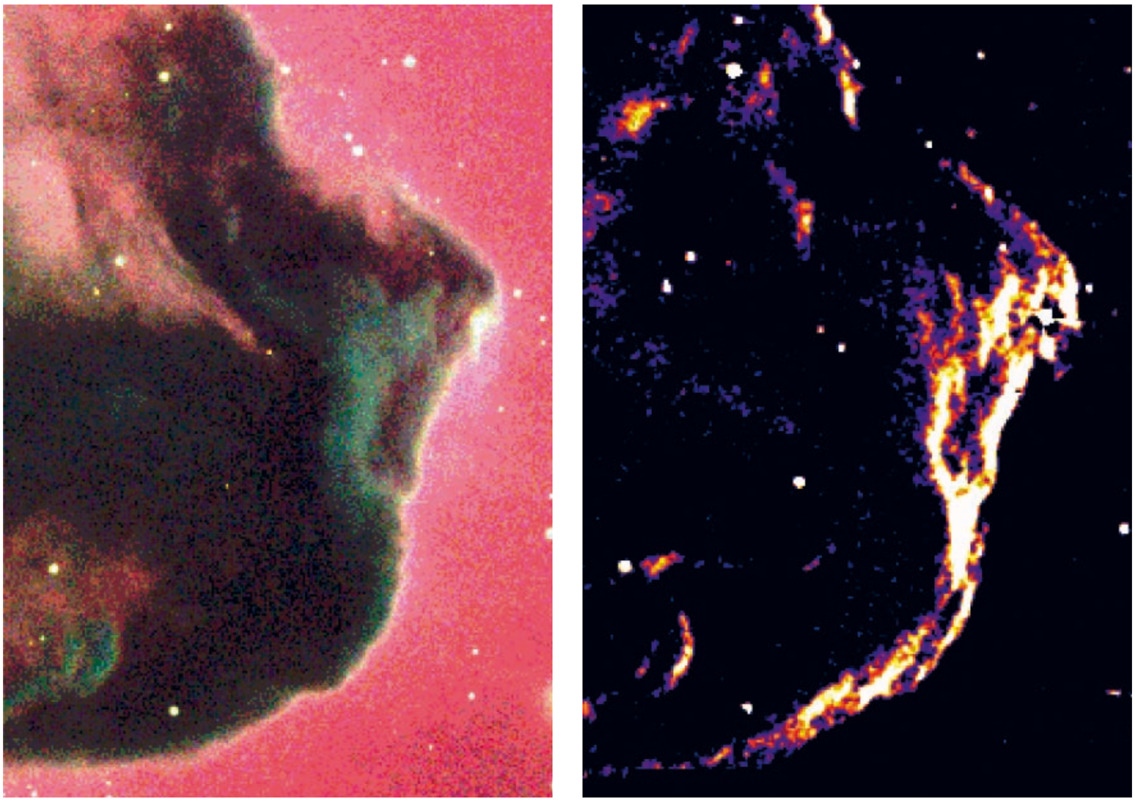

Figure 4: Zoom on the illuminated edge of the Horsehead. **Left:** VLT composite image. **Right:** SOFI image in the H_2 2.12 µm line.

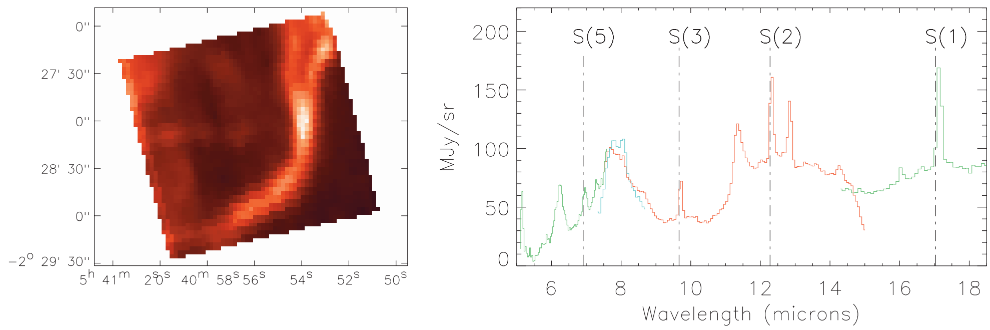

Figure 5: Horsehead nebula observed with Spitzer in the IRS spectroscopic mode. **Left panel:** Map in the continuum emission at 15 µm. **Right panel:** IRS spectrum at the position of the bright filament. Aromatic bands (6.2, 7.7 and 11.3 µm), H_2 (0-0 S(1), S(2), S(3), S(5)) and atomic lines (NeII at 12.81 µm) are easily detected.

From our models also, we conclude that there must be a sharp gradient in density between the H_2 emitting and inner cold molecular layers and Figure 3 also shows our attempt at modelling our SOFI observations together with the ISOCAM data and recent CO and millimetre continuum results (Teyssier et al. 2004, Pety et al. 2004). We conclude that the density rises by an order of magnitude in a layer of thickness 0.02 parsec. The thermal pressure which we infer is a factor of more than one hundred larger than the mean ISM pressure. Whether this is enough to cause gravitational instability is controversial but certainly it is sufficient to compress any pre-existing cores in the molecular cloud. If these are initially close to being unstable, the extra push from the Horsehead PDR may be enough to initiate collapse.

Sub-structures at the edge of the nebula

In the SOFI data, we also discover sub-structures unresolved by ISOCAM. At the edge of the Horsehead, we can in particular clearly distinguish narrow filaments well separated at several places along the interface (see Figure 4). These infrared filaments may represent the PDR edge at different positions along the line of sight. Some of these filamentary structures are also seen in the visible image (see Figure 4), but not everywhere because of the combined effects of extinction and projection.

Future

It is evident that to get further understanding of these regions, one needs additional information on the physical and dynamical conditions from the ionization front to the neutral molecular layer. One step forward in this regard will be supplied by the instruments on the Spitzer telescope and we show in Figure 5 some of the first results from the IRS spectrometer. The H_2 rotational lines will give us a good estimate of the temperature of the neutral warm gas ($T \geq 80$ K), while atomic lines such as NeII at 12.81 µm trace the ionized gas. Sorting out the implications of this will take some time but it is already clear that both higher spectral and spatial resolution are needed in order to understand the role of the Horsehead in triggering star formation. In this regard, the combination of CRIRES in the 1–5 µm range and VISIR at longer wavelengths will be very powerful. CRIRES will have a spectral resolution of up to 3 km s^{-1} and VISIR a spatial resolution of ~ 0.3″ (roughly 120 AU at 10 µm) opening new windows on PDR structure and kinematics. The last word on the Horsehead is far from having been said.

References

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