Solving the Vela pulsar infrared excess problem

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Abstract

Our previous IR studies of the young Vela pulsar with the VLT/ISAAC and Spitzer telescopes have shown a dramatic infrared flux excess over a flat optical-UV spectrum of the pulsar. Such an excess could be caused either by a fall-back disc around the pulsar, possibly formed by supernova ejecta, or by an unresolved extended feature of the pulsar wind nebula, one of which has been detected by us in JH bands within 1.5 arcsec from the pulsar, or by a population of magnetospheric relativistic particles with a steep energy spectrum. To distinguish between these possibilities we have performed deep high spatial resolution observations of the Vela pulsar with the adaptive optics in the HK bands.

Near Infrared Observations

We observed the Vela pulsar in 30-01-2013 in the K_s band with the Gemini Multi-Conjugate Adaptive Optics System (GeMS) and its near-infrared imager, the Gemini South Adaptive Optics Imager (GSAOI), mounted on the Gemini-South telescope and in the H and K_s bands with the VLT/NACO several times in Dec 2012.

Enigmatic feature behind the Vela pulsar

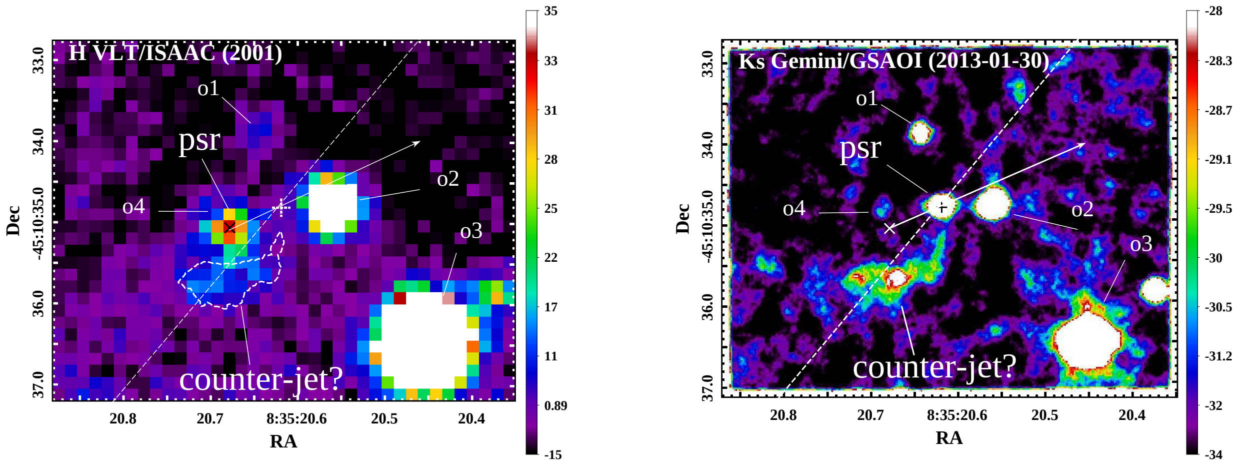

Figure: 5″ × 5″ fragment depicting the Vela pulsar vicinity as seen with the VLT/ISAAC and Gemini/(GeMS + GSAOI) in the H (*left panel*) and K_s (*right panel*) bands. The pulsar and other nearby field objects are marked using notations from Shibanov et al. (2003), except of o4 which is detected only with Gemini. The K_s image is smoothed with a seven-pixel Tophat kernel to better underline the shape of the extended feature, presumably a counter-jet emanating from the pulsar. The long dashed line in the K_s image indicate the direction and position of the counter-jet detected in X-rays. "x" and "+" symbols in both images show the positions of the pulsar at the VLT (2001) and Gemini (2013) observation epochs and the arrow indicate its proper motion path at a 12 yr time base between both observations.

The extended feature near the pulsar was named "counter-jet?" by Shibanov et al. (2003), assuming its possible association with the counter-jet of the Vela pulsar torus-like X-ray PWN. The Gemini AO observations allows us to confirm this feature with higher significance and much better resolve its morphology. It extends southwards from the pulsar by about 2″ along the X-ray counter-jet direction with PA ≈ 130° (Helfand et al. (2001)) marked by the dashed line in Fig. 1. This strongly supports the suggestion that it can indeed be associated with the pulsar counter-jet. In X-rays the counter-jet extends to a much larger distance of about 1′. In the near-IR we see its highly probable origin just near the pulsar. It demonstrates a nonuniform structure with several knots which are reminiscent of the knot structure located only 0.″6 from the Crab pulsar and also projected onto the counter-jet origin of its PWN (Hester et al. (1995)). The putative near-IR jet feature cannot be resolved in *Chandra* X-ray archival images, where it is completely hidden in a point-like spatial profile of the bright pulsar due to a lower spatial resolution in X-rays. It is also not detected in the optical with the HST (Shibanov et al. (2003)) whose spatial resolution is comparable to that of Gemini. This implies that the feature has a very red spectrum.

Spectra of the pulsar and its likely counter-jet

The pulsar K_s flux agrees well with the long-wavelength extrapolation of a flat UV–optical spectrum of the pulsar, making its spectrum similar to that of the Crab pulsar. At the same time, the counter-jet spatially integrated flux, which is about twice as high as that of the pulsar, is compatible with a strong mid-IR excess derived from the *Spitzer* data and fitted early (dot-dashed line) by the sum of the flat pulsar spectrum and a model of a fall-back dusty disc around the pulsar (Danilenko et al. (2011)). We can see now that the apparent IR excess, at least in the K_s band, is dominated by the extended feature, but not a hypothetical disc. The spectral behaviour of the J_sHK_s feature fluxes appears to be non-monotonous with a maximum in the H band. However, if the pulsar spectrum continues to be flat at longer wavelengths and the feature survives there, its flux can continue to increase and dominate the observed excess in the *Spitzer* range as well.

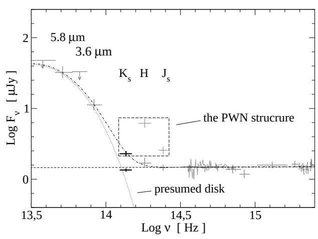

Figure: Spectrum of the Vela pulsar from UV through optical to mid-IR and the IR spectrum of the PWN structure (enclosed in the dashed box). The UV and optical data are from Romani et al. (2005) and Mignani et al. (2007), the JH and mid-IR data are from Shibanov et al. (2003) and Danilenko et al. (2011), the Gemini data are marked by the bold. The dashed line shows the flat UV–optical spectrum of the pulsar, the dotted line shows the expected contribution from the presumed fall-back disk, and the dash-dotted line shows the sum of the two.

Preliminary. Variability of the counter-jet

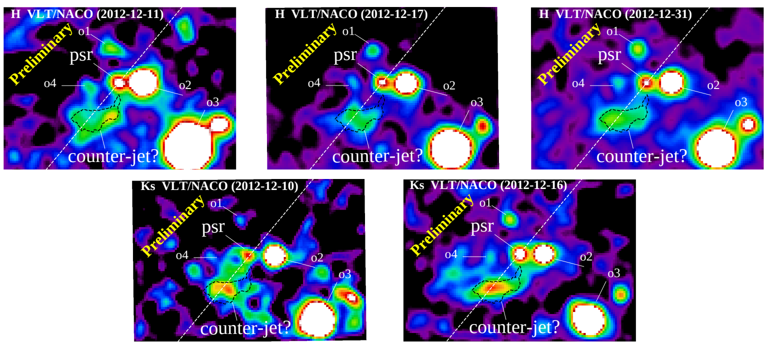

Figure: The Vela pulsar vicinity as seen with the VLT/NACO in the H (*top panels*) and K_s (*bottom panels*) bands at different observation epochs.

Conclusions

The Gemini ground-based observations with the new generation of the AO system, providing a superb image quality comparable to that of the HST, have allowed us to firmly detect, for the first time, the Vela pulsar in the K_s band. The measured pulsar flux is consistent with the extrapolation of the pulsar optical-UV spectrum towards the IR, showing that the spectrum remains flat in this range and does not show any excess suggested early by lower spatial resolution IR data. The AO observations also enabled us to much better resolve the feature extended immediately behind the pulsar. The feature is significantly brighter than the pulsar in the K_s band and likely to be the main source of the strong IR flux excess in the pulsar spectrum derived from the mid-IR data. This likely disregards alternative interpretations of the excess discussed by Danilenko et al. (2011), namely fall-back disk and complicated emitting particle distribution function, but without high spatial resolution longer wavelength data we cannot still completely exclude them. However, now they appear to be more artificial.

The elongation of the extended feature in the direction of the X-ray counter-jet and backward the pulsar proper motion suggests that it can be either the near-IR counterpart of the pulsar X-ray counter-jet or a tail. This is supported by the compact and relatively bright knot-like structures within the feature, which are reminiscent of the well known optical-near-IR knot within the south-east jet of the Crab pulsar. The red spectrum of the Vela counter-jet counterpart candidate similar to that of the Crab knot (Sandberg & Sollerman (2009)) also favours this interpretation. The observed chain of knots can also imprint past episodes of the Vela pulsar sporadic activities.

The Crab knot (Sandberg & Sollerman (2009)), and Vela jets (Pavlov et al. (2001)) are known to demonstrate a high time variability even in a week scale. Preliminary VLT/NACO data obtained at different epochs shows evidence of the spatial variability of the feature. This serve as a strong evidence for its PWN nature.

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