# The CRIRES Search for Planets at the Bottom of the Main Sequence

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**We present the first results obtained from our ongoing search for planets around very low-mass stars and brown dwarfs using radial velocities measured with the CRIRES spectrograph on the VLT. High-precision radial velocity measurements for a large sample of these previously neglected stars are enabled by observing at near-infrared wavelengths and using a new type of gas cell that we have developed. Unprecedented long-term near-infrared radial velocity precisions of ~ 5 $ms^{-1}$ have been demonstrated using CRIRES with the cell. As a first scientific result, data obtained for the very low-mass star VB 10 have been used to refute a claimed planet detection based on astrometry. These results demonstrate the unique sensitivity of our methodology, and confirm its power to detect planets, including potentially habitable ones, around the most numerous stars in the Galaxy.**

The vast majority of known exoplanets have been detected around solar-type stars with spectral types F, G or K. However, the vast majority of stars in the Solar Neighbourhood, and likely our entire Galaxy, are M or later type dwarfs. Indeed, current estimates suggest that at least 75 % of stars within 10 pc of our Solar System are M dwarfs. Furthermore, the very lowest-mass stars, those with $M < 0.2\ M_\odot$, make up more than 50 % of the M dwarf population. Therefore, objects at the bottom of the main sequence constitute a very significant fraction of potential planet hosts, and it is imperative that we characterise the nature of the planetary systems around them in order to constrain the Galactic planet census.

The paucity of detections of planets around M type and later dwarfs is due to two factors. The first reason is that these stars are intrinsically very faint at the wavelengths typically used for planet searches due to their low masses. For example, a Sun-like star at 10 pc will have a visual magnitude of 4.8, while M3, M6, and M9 dwarfs would have visual magnitudes of 11.1, 16.5, and 19.5 respectively. As a consequence of this, many fewer late-type stars have been included in planet search programmes than brighter solar-type stars, and only stars with spectral types down to M3 have been included in planet searches in any substantial number to date. For example, the sample of 40 stars in a long-term radial velocity planet search programme specifically targeting low-mass stars that utilised UVES at the VLT only included two objects with masses below 0.2 $M_\odot$, and only three with masses below 0.35 $M_\odot$ (Kürster et al., 2009).

Another reason why many planets have not been found around late-type stars is that giant planets seem to be rare around the few such objects that have been targeted by planet searches. This result is consistent with the predictions of the so-called “core accretion” model of planet formation, which posits that a critical part of the formation of gas giants is the build up of a rock and ice core about ten times the mass of the Earth before the gas in the protostellar disc is dispersed by the central star’s wind. It is thought that it is less likely that such cores can form fast enough around low-mass stars mainly because they host correspondingly low-mass circumstellar discs. Ultimately, what this means is that the easiest planets to detect with current methods (i.e., primarily the radial velocity method) are rare around late-type stars due to their low mass.

A directly testable prediction of the core accretion model is that giant planets should be vanishingly rare around the very lowest-mass stars. By contrast, the competing model for giant planet formation, the so-called “gravitational instability” mechanism, predicts that gas giants should be just as common around very low-mass stars as solar-type stars. Therefore, low-mass stars offer the potential for definitively establishing the efficiency of the two competing theories of giant planet formation. Furthermore, the search for planets around low-mass stars can offer further insight into planet formation and evolution processes. Comparing the overall mass function of planets around low-mass stars and higher-mass stars can yield constraints on the timescales of planet growth, planet migration, and protoplanetary disc depletion.

Low-mass stars are also interesting potential hosts for habitable exoplanets that could be detected and studied in the near future, despite their currently neglected status. Low-mass stars of course have correspondingly lower luminosities, and this suggests that their habitable zones are closer in than for their higher-mass counterparts. Therefore, low-mass planets in the habitable zones of low-mass stars will yield much larger signals in radial velocities and also have a much higher probability of transiting. These factors taken together with the overwhelming ubiquity of low-mass stars suggest that the nearby low-mass stars have the best potential for finding a transiting habitable planet, and studying the atmosphere using the technique of transmission spectroscopy using future facilities like the James Webb Space Telescope.

Given the unique opportunities that very low-mass stars offer for advancing our understanding of exoplanets, we were recently motivated to initiate the first comprehensive search for planets around these kinds of stars. This survey is being carried out in Periods 82–85 as a Large Programme with 33 nights of visitor mode time on the VLT. Our methodology is to use high-precision radial velocities measured for the first time in the near-infrared (NIR) spectral regime. The advantages of the NIR for radial velocity measurements are that it is possible to obtain high-resolution and high-signal-to-noise spectra of very low-mass stars at these wavelengths, and also that the effect of activity-induced “jitter” is reduced relative to the visible. This later advantage is particularly important because low-mass stars are generally much more active than solar-type stars and this can hinder the detection of planets with the radial velocity method. For this work we are taking advantage of the one-of-a-kind instrument CRIRES, which is mounted on the VLT's Unit Telescope 1 (UT1). Of all available NIR spectrographs in the world, only CRIRES has the resolution, throughput and large spectral format necessary to obtain spectra of very low mass stars suitable for high-precision radial velocity measurements.

## The planet search sample

We have selected 36 of the nearest very low-mass stars and brown dwarfs for our CRIRES planet search. See Figure 1 for a summary of their physical properties. We are concentrating primarily on stars with masses less than 0.2 $M_{\odot}$, and that are too faint and/or display too much activity-related jitter for efficient high-precision radial velocity measurements in the visible using existing instruments. A few higher-mass stars that are known to be extremely active were included in this first survey to characterise the reduction in jitter seen when going from the visible to the NIR. We are obtaining contemporaneous visible wavelength radial velocity measurements of some of these stars using the Hobby Eberly Telescope for this aspect of the project.

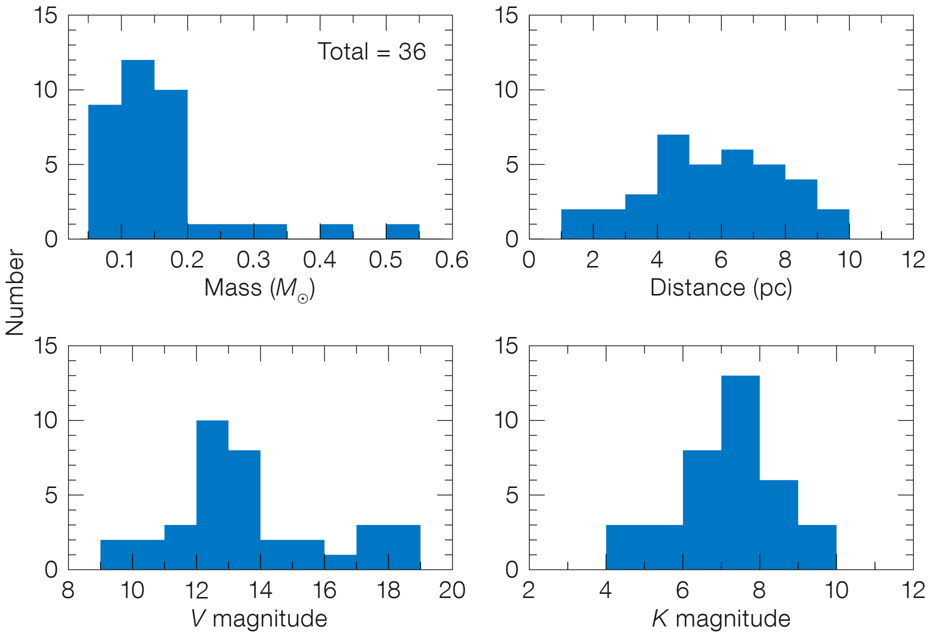



Figure 1. Summary of the physical properties of our planet search targets among low-mass stars.

## A new gas cell

The potential of the NIR for high-precision radial velocity studies of low-mass stars had previously been discussed extensively before this project began. However, no previous work had achieved a long-term NIR radial velocity precision on a star other than the Sun within an order of magnitude of the precision that is routinely obtained in the visible. The main reason for this up until recently was the lack of high-resolution NIR spectrographs on large telescopes that could deliver sufficient spectral coverage in a single shot. Indeed, the possibility of high-precision NIR radial velocities was one of the motivations for CRIRES during the later part of its design phase. The commissioning of this instrument in 2006 opened the door for high-precision radial velocity measurements of very low-mass stars.

The final missing ingredient for measuring high-precision NIR radial velocities was the lack of a suitable calibration method. Useful lines from available emission sources, like thorium–argon (ThAr) lamps, are infrequent in the NIR relative to the visible and there are many CRIRES settings where no lamp lines exist. Furthermore, as a long slit spectrograph, CRIRES experiences significant variations in illumination on a variety of timescales. So, although CRIRES could, in principle, be fed with light from an emission lamp, no appropriate lamps exist currently and anyway such a calibration technique would not track all the necessary effects for high-precision radial velocity measurements.

The success of the "iodine cell" in the visible suggested that a gas cell could be a useful way to calibrate CRIRES, and the instrument was designed to use this calibration method. However, at the time of the CRIRES commissioning the questions of which gas or combination of gases to use, and which specific wavelength region in the NIR to observe, were still unsolved. The main constraint for the gas cell method is that the gas or gases in question should exhibit numerous sharp and deep lines in a wavelength interval where the stars targeted for radial velocity measurements have lines as well. Ideally, this region would also be free of atmospheric lines. However, this is a particularly challenging requirement in the NIR due to the prevalence of strong atmospheric lines even in the traditional windows between water absorption bands. A significant bonus would be if the cell did not present a safety hazard to people or other equipment if it broke during the course of its use. For CRIRES specifically, there was also no room to include a temperature heating or stabilisation apparatus such as is needed for iodine cells, which are typically heated to 50–70 °C and held to within 0.01 °C of a fixed temperature. So any potential cell would have to work at the temperatures normally seen in the telescope dome (~ 10 °C) and be immune to modest variations in the temperature.

With our interest in carrying out a high-precision radial velocity planet search of very low-mass stars in the NIR, we were motivated to work on the problem of building a useful gas cell. After combing line lists and performing simulations we came to the conclusion that simple ammonia ($^{14}NH_3$) could provide the desired calibration. Ammonia is in its gaseous state at room temperature and exhibits a rich molecular spectrum in the NIR even with the relatively low column densities possible in a cell to be used at an astronomical observatory. Simulations using calculated synthetic spectra suggested that the expected temperature variations the cell would see in CRIRES (± 10 °C maximal) would only result in a systematic radial velocity shift of ~ 1 $ms^{-1}$, which is a sufficient level of stability for our purpose.

Although ammonia exhibits lines in different regions of the NIR, even CRIRES yields only relatively small wavelength coverage in a single exposure. Therefore, a careful consideration of the region for observations was necessary in parallel with the choice of a gas for the calibration cell. We chose to make observations in a window in the *K*-band for several reasons: very low-mass stars exhibit numerous sharp and deep lines in this wavelength region suitable for radial velocity measurements; ammonia exhibits a number of lines useful for calibration in this wavelenght range. Unfortunately, the window in which we are observing also contains a significant number of absorption lines arising from telluric methane and water. This was already known before we began our work. High-precision radial velocity measurements are usually made by avoiding regions containing telluric lines due to the expectation that these lines will exhibit variability on the order of a few to tens of $ms^{-1}$, or that they are at least difficult to model properly. However, the lack of another obvious method for achieving the desired calibration meant that a more flexible approach was called for. We decided that using an ammonia cell in the *K*-band and including direct modeling of the telluric contamination was a good option considering all the competing issues.

The ammonia cell that we ultimately built and are using for our CRIRES planet search is a glass tube with chemically fused windows that has a length of 17 cm, and diameter of 5 cm. The pressure of the ammonia gas in the cell is 50 mb at 15 °C. In principle, the bonds holding the windows on to the body of the cell should remain sealed for more than ten years. A picture of the cell in the laboratory is shown in Figure 2.

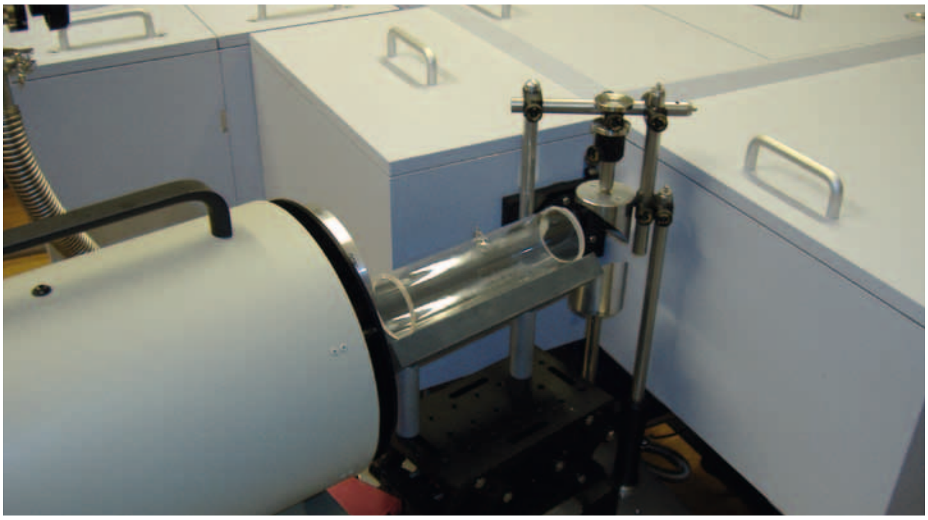


Figure 2. Picture of the ammonia cell being measured with a laboratory Fourier Transform Spectrometer (FTS) at Lund Observatory. The cell is being illuminated with light from a 1200.0 °C blackbody source (grey cylinder on the left). The FTS is in the vacuum box at the upper right.

## Using the gas cell with CRIRES

Our ammonia cell was commissioned by ESO staff as a visiting instrument in CRIRES during the early part of P82, and it has been in routine use since February 2009. The cell is mounted inside the CRIRES warm optics box in an aluminium housing on a carriage that moves the cell in and out of the telescope beam. The carriage has room for two gas cells at one time and CRIRES is normally equipped with cells filled with $N_2O$ and CO. These cells are part of the normal calibration plan, but are not useful for high-precision radial velocity work because they do not yield lines in regions where stars also have useful lines. One of the standard cells has to be removed so that our ammonia cell can be inserted. All observations to date with our cell have been performed in visitor mode so as not to impede the necessary calibrations for service mode programmes and regular instrument monitoring.

The gas cells in CRIRES sit just in front of the Nasmyth focus de-rotator in the converging f/15 beam from the telescope. At this location, they are in front of all the spectrograph optics, as well as the instrument's integrated AO system. Our observations of a star for radial velocity measurements are obtained with the ammonia cell in the beam, which causes the absorption lines of the cell to be imprinted on the stellar spectrum. The cell lines, whose position and shapes are well known, serve as a fiducial to precisely establish the wavelength scale and point spread function of the instrument at the time of the observation independently for each of the obtained spectra during analysis of the data.

We have performed laboratory measurements of our ammonia cell using the Lund Observatory Bruker IFS125 HR Fourier Transform Spectrometer (FTS) to obtain the characteristic spectrum that is needed for the radial velocity measurements during analysis of the data (see Figure 2). The obtained FTS spectrum has a resolution $R$ = 620 000 and measured $S/N$ > 700 in the continuum at 2.3 μm. A plot of this spectrum in the wavelength region at which we are observing is shown in Figure 3.

The primary FTS measurement was obtained with the cell cooled to 13 °C. This temperature is close enough to the temperatures the cell experiences in CRIRES given the stability of ammonia. In addition to this spectrum, we also obtained measurements of the cell at 24 °C

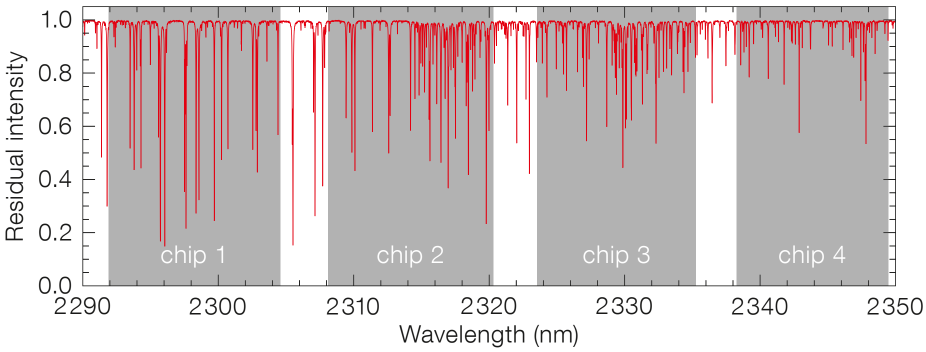
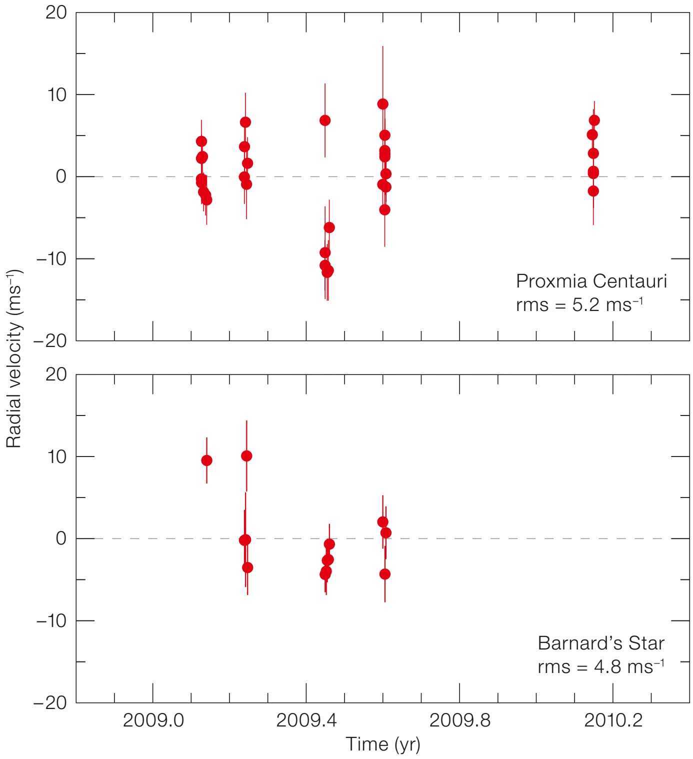



Figure 3 (above). Spectrum of the ammonia cell in the observed wavelength region at $R$ = 100 000. The grey boxes indicate the wavelength coverage of the four chips in the CRIRES detector mosaic.

Figure 4 (below). Radial velocities of two stars, with velocities known to be constant from visible range measurements, observed with CRIRES using the ammonia cell.




on two separate occasions 13 months apart — once right before the cell was originally handed over to ESO in August 2008 and again after our programme had started in September 2009. Comparison of these data reveals no change in the cell's spectrum, which supports our assumption of the cell's stability.

## Tests of radial velocity precision

In addition to the very low-mass stars we are monitoring as part of our ongoing planet search, we have also frequently observed Proxima Centauri (GJ 551) and Barnard's Star (GJ 699) to characterise the performance of the cell and our radial velocity measurement algorithms. These stars are two of the few very low-mass stars for which it is possible to obtain high-precision radial velocity measurements in the visible wavelength range (due to their being very nearby, and thus bright even at visible wavelengths), and previous work has shown their radial velocity to be constant at the level of 3 ms$^{-1}$.

The radial velocities we have obtained for these stars between February 2009 and February 2010 are shown in Figure 4. These data exhibit a typical root mean square (rms) scatter about a constant value of ~ 5 ms$^{-1}$. This demonstrates that we have obtained the long-awaited breakthrough in NIR radial velocity precision on very low-mass stars using CRIRES with our ammonia cell. The details of our radial velocity measurement technique and more extensive tests of the obtained precision can be found in Bean et al. (2010b).

## First result: no giant planet for VB 10

The unique capability of CRIRES when used with our ammonia cell to obtain high-precision radial velocities of low-mass stars is demonstrated by the case of VB 10. This object lies right at the boundary between stars and brown dwarfs (estimated mass is ~ 0.08 $M_{\odot}$). It is very faint in the visible ($V$ = 17.3) despite being one of the closest examples of its spectral type. However, it is reasonably bright in the NIR ($K$ = 8.8) due to its extreme redness. Pravdo & Shaklan (2009) reported the detection of a giant planet around this star based on ground-based astrometry. This would have been the first detection of a planet around a nearby very low-mass star, and would also have been the first astrometric discovery of an exoplanet.

We obtained 12 radial velocity measurements of VB 10 over four epochs using CRIRES with our ammonia cell during the first year of our programme. These velocities are shown in Figure 5. Our measured velocities exhibit an rms dispersion of only 10 ms$^{-1}$, whereas the expected signal from the proposed giant planet is ~ 1 kms$^{-1}$. We were able to completely rule out the existence of the proposed planet using the observed constancy of the radial velocities (Bean et al., 2010a).

For comparison, other groups have obtained radial velocity measurements of VB 10 in an attempt to detect the planet as well. These measurements have been done in the visible using the Magellan telescope, and in the NIR using Keck. However, even though these other measurements were made with similarly sized telescopes and similar exposure times as our measurements, they only had precisions of ~ 300 $ms^{-1}$. This clearly demonstrates both the superiority of CRIRES among existing NIR spectrographs, and the power of our observational methodology for very low-mass stars.

## Outlook

Our search for planets around very low-mass stars is continuing until at least the end of P85 and we have recently proposed to continue the programme for another two years. One of the goals of the new programme is to continue monitoring the 36 objects surveyed in the previous study in order to confirm planet candidates that we have identified around some of the stars, and to probe for lower-mass and longer-period planets around all the stars. The new measurements should enable us to be sensitive down to even terrestrial-mass planets in the habitable zones around many of the stars we are targeting. We also aim to widen our survey to include 30 new targets that we will search for gas giant companions in a sort of shallow–wide survey.

In addition to our work with CRIRES, we are also beginning a similar survey in the northern hemisphere using the NIR spectrograph IRCS on the Subaru telescope with a copy of our ammonia cell. The radial velocity precision obtained with this facility will be significantly less than with the VLT + CRIRES due to the IRCS's lower spectral resolving power (20 000) and throughput, but it will still be useful to search low-mass stars for gas giant

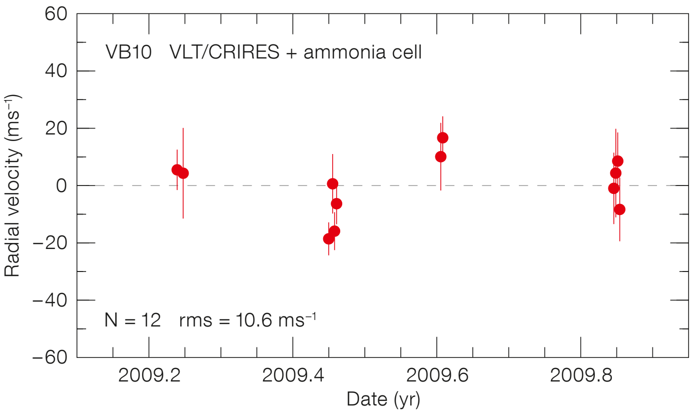



Figure 5. Radial velocities measured for the very low-mass star VB 10 with CRIRES using the ammonia cell.

planets. Together, the new CRIRES programme and the Subaru programme are volume complete for all known stars with masses < 0.2 $M_{\odot}$ and spectral type earlier than T0 out to 10 pc. Therefore, we are adding important information to the census of planets around nearby stars.

Technically speaking, our results have shown that obtaining NIR radial velocity precisions comparable to those which are routinely obtained in the visible is possible, and we see no reason why a level of precision of 1 $ms^{-1}$ could not be obtained in the future with a new approach or instrument. Our current measurements are limited by the presence of telluric lines in the window in which we are observing, and it is likely we would be doing about a factor of two better if these lines were not present. Therefore, if a new type of gas cell for the NIR was designed that yielded useful calibration lines where interesting stars also have lines and where the Earth's atmosphere does not, then that would probably give a boost in performance. However, our experience suggests such a breakthrough is unlikely. Instead, it is more likely that improving on our results will require applying the HARPS concept of building a highly stabilised instrument for the NIR. Indeed, such new instruments are currently being considered for the immediate future for telescopes in the 4-metre class range, and in the longer-term for 8–10-metre class telescopes and even ELTs.


### Acknowledgements

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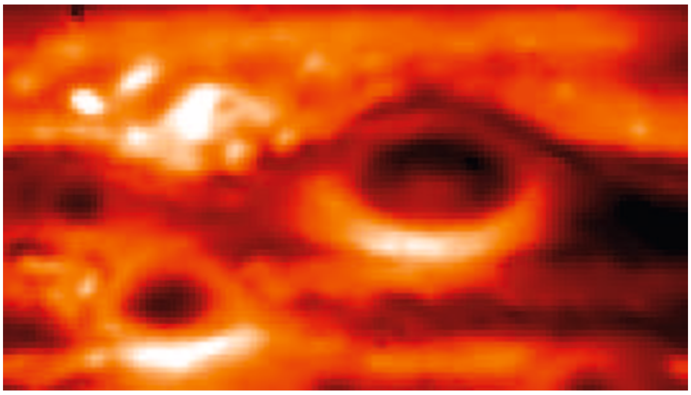

Image of the Great Red Spot on Jupiter taken with the VLT Imager and Spectrometer for mid Infrared (VISIR). The structure of the Great Red Spot in the thermal emission at 8–13 microns is revealed in this image. See release eso1010 for more details.