Status of known T type sources towards the σ Orionis cluster

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Abstract. We present the characterization of the three T type candidates (S Ori 70, S Ori 73, and S Ori J053804.65−021352.5) lying in the line of sight towards σ Orionis ($\sim$3 Myr, $\sim$352 pc, solar metallicity) by means of near-infrared photometric, astrometric, and spectroscopic studies. H-band methane images were collected for all three sources using the LIRIS instrument on the 4.2 m William Herschel Telescope. J-band spectra of resolution $\sim$500 were obtained for S Ori J053804.65−021352.5 with the ISAAC spectrograph on the 8 m Very Large Telescope (VLT), and public low resolution (R$\sim$50) JH spectra obtained with the Wide Field Camera 3 (WFC3) on board the Hubble Space Telescope (HST) were employed for the spectroscopic classification of S Ori 70 and 73. Accurate proper motions with a typical uncertainty of $\pm$3 mas yr^{-1} were derived using ancient images and new data collected with ISAAC/VLT and WFC3/HST. The three objects were spectroscopically classified as T4.5 $\pm$ 0.5 (S Ori 73), T5 $\pm$ 0.5 (S Ori J053804.65−021352.5), and T7$^{+0.5}_{-1.0}$ (S Ori 70). These spectral types agree with the H-band methane colors. The proper motions of S Ori 70 and 73 are larger than that of the cluster by $>4\,\sigma$. The proper motion of S Ori J053804.65−021352.5 is consistent with a null displacement during the time interval of 7.03 yr.

1. Introduction

The T type sources are among the coolest population of our Galaxy. Their study in young clusters, like σ Orionis ($\sim$3 Myr (Zapatero Osorio et al. 2002; Sherry et al. 2008), low extinction (Lee 1968; Béjar et al. 2004), solar metallicity (González Hernández et al. 2008), $\sim$300–

450 pc (Brown et al. 1994; Caballero 2008)), are key to understand their differences with high-gravity field T type dwarfs and to define a reliable cluster mass function at planetary masses. Our main goal is to perform a complete photometric, spectroscopic and astrometric characterization of the identified methane sources in the line of sight of the σ Orionis cluster. These dwarfs at the age and cluster distance would be some of the lowest mass cluster members.

2. Target selection

Towards the σ Orionis cluster, there are identified three T type candidates: S Ori 70 (Zapatero Osorio et al. 2002), S Ori 73 (Bihain et al. 2009) and S Ori J053804.65−021352.5 (Peña Ramírez et al. 2012; hereon J0538−0213). In the case of S Ori 73, this source lacks spectroscopic data in refereed published publications[1]. J0538−0213 lacks any proper motion or spectroscopic characterization prior to this work. We also have collected images of 15 known field T type dwarfs. All of them with spectral types estimated in the near infrared and ranging from T0 to T7. These sources will be used to calibrate the observed $H - CH_{4\mathrm{on}}$ color as a function of spectral type.

3. Observations

3.1 Near–infrared spectroscopy

J-band near-infrared spectroscopy of J0538−0213 was obtained using the Infrared Spectrometer And Array Camera (ISAAC; Moorwood 1997) at the Very Large Telescope. Our data were obtained in the low-resolution mode with a slit width of $1\farcs0$ and centered at 1.25 μm. This instrumental configuration yielded a spectral nominal dispersion of 3.49 Å pix^{-1}, a resolving power of about 500 at the central frequency, and a wavelength coverage of 1.09–1.42 μm. ISAAC observations of J0538−0213 were collected with a seeing of $0\farcs7$–$1\farcs0$ on 2012 December 4.

J0538−0213 was observed in an ABBA nodding pattern twice, yielding a total on-source integration time of 1.33 h using a bright star (J=17.5 mag) as reference to align the slit. To account for absorption by the Earth's atmosphere, a telluric standard of warm spectral type B was observed immediately after the target and as close to the same air mass as possible, within ±0.1 air masses. Pairs of nodded target frames were subtracted to remove the background emission contribution and then divided by the corresponding flat field. Individual frames were stacked together to produce higher signal to noise spectra. The extracted spectra were calibrated in wavelength, corrected for instrumental response and telluric absorption using data of the telluric standard. Finally, the data were multiplied by black body curves of appropriate temperatures to restore the spectral slope.

S Ori 70 and 73 have publicly available spectroscopic data from the Mikulski Archive for Space Telescopes. As part of the program number 12217 (principal investigator: P. Lucas), low-resolution, slitless spectra were obtained using the G141 grism and the Wide Field Camera 3 (WFC3) onboard the Hubble Space Telescope (HST). The integration time was 40

[1] See also www.star.herts.ac.uk/mindthegap/posters/lucas_poster.pdf in August 2014

min for each target, which corresponded to the duration of one orbit. Observations followed a four-point dither pattern to remove cosmic rays. Data were reduced using the aXe software package (Kümmel et al. 2009), which included flat-field correction, background subtraction, optimal extraction of the spectra using an aperture of 6 pix ($0.''7$), and wavelength and flux calibrations. The final WFC3 JH spectra have a spectral nominal dispersion of 46 Å pix^{-1}, a resolving power of about 50 at the central frequency (1.39 μm), and a wavelength coverage of 1.08–1.70 μm.

3.2 Near–infrared imaging

We obtained photometric data using the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS; Manchado et al. 2004) on the William Herschel Telescope. For the LIRIS observations we follow a nine-point dithering pattern with offsets in both directions of $15.''0$ using the H and $CH_{4\rm on}$ filters. For calibration purposes, together with the methane imaging of the known T type dwarfs in the line of sight of σ Orionis, we have collected images of 15 field T type dwarfs (T0 to T7). LIRIS data were collected with a clear weather conditions and a seeing of $0.''65$–$1.''83$ on 2007 December 14, 16; 2009 Jan 14, Dec 15, and 2011 Dec 30, 31.

Data reduction includes flat field corrections and sky subtraction. Individual images were aligned and combined to produce deep data in the H and $CH_{4\rm on}$ bands. We performed aperture and point spread function photometry, fitting gaussian functions to $\sim$15 isolated stars per pointing. The instrumental magnitudes in the H band were calibrated using sources from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and the UKIRT Infrared Deep Sky Survey (DR8 UKIDSS; Lawrence et al. 2007) catalogues. The photometry of these calibrators was converted to the Manua Kea Observatory photometric system using the expressions given in Leggett et al. (2006). The photometric uncertainties of the sources used as calibrators were typically below 0.1 mag.

The LIRIS $CH_{4\rm on}$ filter was calibrated relative to the H band following the procedure described in Goldman et al. (2010) and Peña Ramírez et al. (2011). Objects with H band magnitudes between 13 and 16 (probably Galactic stars of spectral types G–K according to their 2MASS and UKIDSS colors) were forced to have null $H - CH_{4\rm on}$ colors. The typical dispersion in this procedure was 0.04 mag, which was added quadratically to the $H - CH_{4\rm on}$ colors.

For S Ori 70 and S Ori 73 we also have retrieved public HST/WFC3 F140W images. The wide WFC3 F140W filter covers the gap between the J and H bands that is inaccessible from the ground. Standard calibrations were applied (dark current subtraction, linearity correction, and flat fielding) to all of the individual readouts of the WFC3 near infrared exposures. HST/WFC3 exposures were retrieved as the combined image from the individual processed readouts (FLT output product file).

4. Results and final remarks

4.1 Spectroscopic classification

Figure .1 illustrates the final ISAAC spectrum of J0538−0213. It is shown together with known field T4–T6 dwarfs from the literature. The processed HST/WFC3 spectra for S Ori 70 and S Ori 73 are presented in Figure .2.

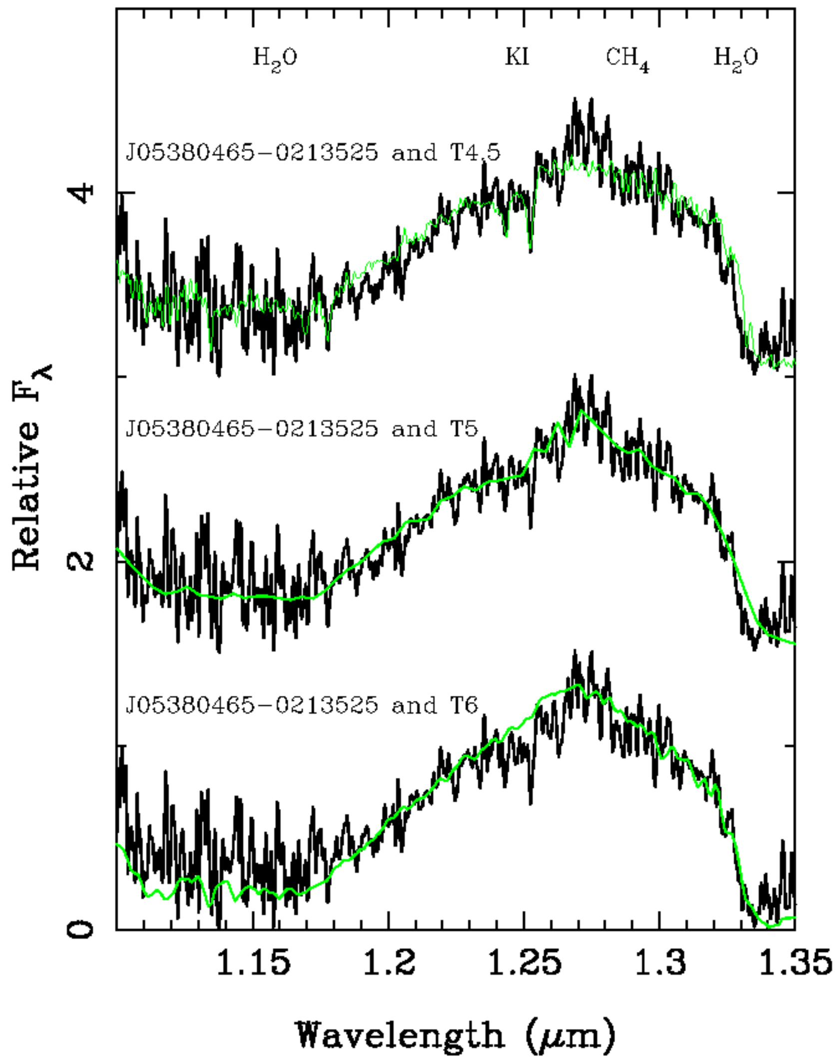

Figure .1: The ISAAC J-band spectrum of J0538−0213 (black) is shown in comparison with field T dwarfs from the literature (green). The T4.5 field dwarf has a similar spectral resolution as our data, while the other two field dwarfs have lower spectral resolution. The most prominent features are indicated at the top. All spectra are normalized to unity at 1.28–1.32 μm. A constant offset of 1.5 and 3.0 was added for the clarity of the figure.

The overall spectral shape of J0538−0213 in the J-band reproduces the spectrum of a T type dwarf. The K I doublet at around 1.25 μm is detected. From our spectroscopic data we derive for this source a spectral type of T5±0.5, based on the strong water vapor and methane absorptions of its J-band spectrum, and in comparison to field T dwarfs from the literature showed in Figure .1.

The collected HST spectra in the range 1.1–1.7 μm for S Ori 70 and S Ori 73 do not appear to differ from the spectra of other T type dwarfs of the field. We estimate a $T7^{+0.5}_{-1.0}$ spectral type for S Ori 70 and T4.5±0.5 for S Ori 73. These spectral type estimations for

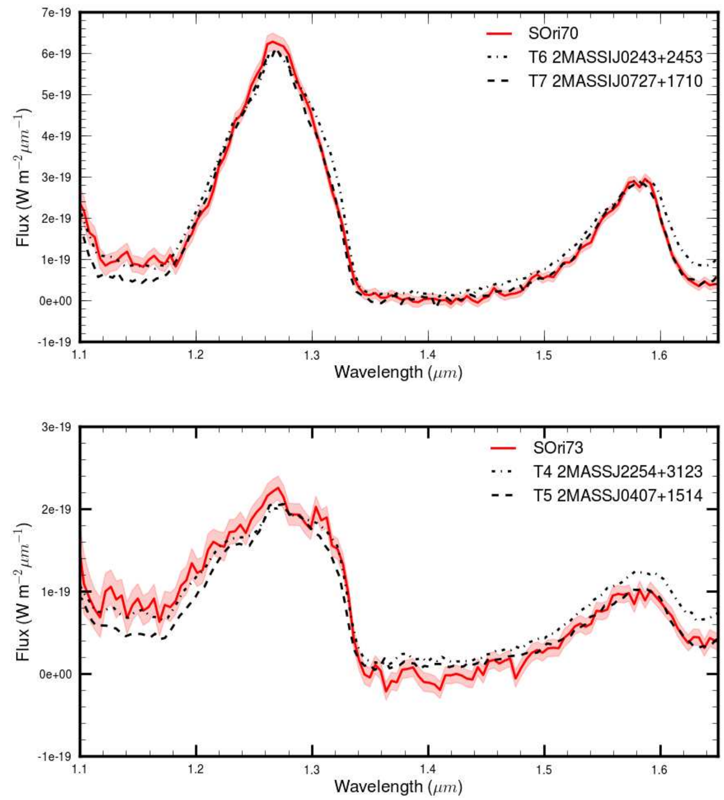

Figure .2: HST/WFC3 spectrum of S Ori 70 and S Ori 73 using the G141 prism plotted (solid red line). Uncertainties in flux are plotted within a red shaded area. The comparisons of S Ori 70 (left panel) and S Ori 73 (right panel) with field T type dwarfs are indicated with dashed/dot dashed lines. All spectra are normalized at the J–band peak between 1.262–1.274 μm.

the two of the known T type dwarfs towards the σ Orionis cluster are consistent with the spectroscopic data for S Ori 70 and methane imaging of S Ori 73 reported in the literature (Zapatero Osorio et al. 2002; Peña Ramírez et al. 2011). At the wavelength range studied neither of the two T type dwarfs show clear spectroscopic features of low gravity atmospheres.

4.2 Methane filter spectral types

To estimate the spectral type of J0538−0213 through methane imaging, we will use as calibrators the $H - CH_{4\mathrm{on}}$ colors of the field T dwarfs observed with the same instrumentation. For all the observed field T dwarfs, the H band photometry published in the literature and the one obtained with LIRIS are in agreement within the error bars.

Figure .3 shows the final $J - H$ versus $H - CH_{4\mathrm{on}}$ color–color diagram built for the T type sources towards the σ Orionis cluster and the field T type dwarfs. The locations of S Ori 70, S Ori 73 and J0538−0213 are highlighted in the diagram. The same figure also presents the average values of the spectrophotometric integration of T type spectra from

Knapp et al. (2004), Chiu et al. (2006) and Golimowski et al. (2004), which were obtained using the transmission curves of LIRIS H and $CH_{4\mathrm{on}}$ filters. Photometric data of the T type sources towards the σ Orionis cluster are gathered in Table .1.

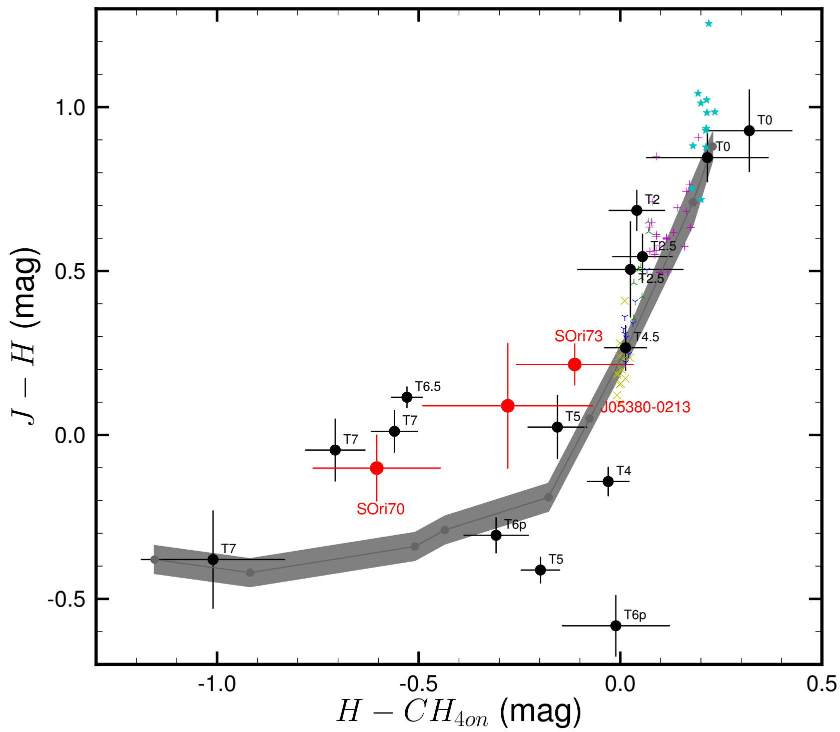

Figure .3: $J - H$ versus $H - CH_{4\mathrm{on}}$ color–color diagram (including the H and $CH_{4\mathrm{on}}$ LIRIS bands) for S Ori 70, S Ori 73, J0538−0213 (red symbols) and the observed T type field sources (black points).The mean LIRIS methane color for F (yellow), G (blue), K (green), M (magenta) and L (cyan) type sources from their spectrophotometric integration is shown. The line resulting from the spectrophotometric integration of field T dwarf spectra is shown as a solid grey line, the shaded area stands for the uncertainties related with the $J - H$ color. The grey dots over this line correspond to T0.5, T1, T3, T4, T5, T6, T7, T8, and T9 field dwarf spectral types.

Based on the location of S Ori 70, S Ori 73 and J0538−0213 in Figure .3, S Ori 70 is consistent with a ∼T6-T7 type dwarf, the S Ori 73 spectral type is consistent with a ∼T4 methane source and for the T type candidate J0538−0213, we estimate an spectral type of $\mathrm{T5}^{+1.5}_{-1.0}$. The spectral types spectrophotometrically estimated are in general agreement with the spectral types derived from the spectroscopic data and with the values given in the literature (Zapatero Osorio et al. 2002; Peña Ramírez et al. 2011). The J0538−0213 candidate seems to be later than S Ori 73 but earlier than S Ori 70, indicating an intermediate effective temperature between S Ori 73 and S Ori 70.

4.3 Astrometry

To perform our astrometric analysis for S Ori 70 we have used Keck–I/NIRC K_s band data (2002 February 25, pixel scale of 0.″157) presented in (Zapatero Osorio et al. 2002, 2008) as first epoch data and the HST F140W band image (2010 September 5, pixel scale 0.″128) as second epoch. The T type dwarf was detected with a S/N of 7 and 286 in the peak in relation with the background/instrumental noise in the first and second epochs, respectively. The time baseline given by these two images is 8.68 yr.

The proper motion of S Ori 73 was calculated by using an ISAAC J band image (2001 December 10, pixel scale 0.″15) described in Caballero et al. (2007) as first epoch image and the HST F140W band image (2010 October 6) as second epoch data. S Ori 73 was detected with a S/N ratio of 11 in the first epoch image and 166 in the second epoch image. The time separation between first and second epoch data is 8.82 yr.

For J0538−0213, the proper motion measurements used data from the UKIDSS survey (J band image) as first epoch (2005 November 22, pixel scale 0.″4) and the acquisition image of our ISAAC J band spectroscopical observations as second epoch data (2012 December 04, pixel size 0.″147). The candidate was detected in the UKIDSS image with a S/N ratio of 5 and in the ISAAC image with S/N=14. These two epochs give a lapse of 7.03 yr to perform the J0538−0213 proper motion measurement.

The proper motions were calculated by the comparison of the relative positions of each source in pixels with respect to 6–20 non-resolved sources within an area of 0.25–6.25 arcmin^2. All the reference sources show S/N ratios above 15 in both epoch images. A pixel third-order polynomial transformation (order two in the case of S Ori 70) between epochs was calculated. The dispersion of all the transformations was typically of 0.2 pix for both the x and y axes after rejecting reference sources that deviate by more than 3σ from null motion. The resulting pixel shifts were converted into proper motions by taking into account the time difference of the data, the pixel scale values of the images, and the orientation of the frames. In Figure .4 we have shown the results of the proper motion measurements of S Ori 70, S Ori 73, and J0538−0213; the estimated values are gathered in Table .1. The proper motion uncertainties were calculated by adding quadratically the dispersion in the polynomial transformation and the errors in the targets centroids (0.02–0.13 pix).

The proper motion measurements of S Ori 70 and S Ori 73 are consistent at the level of 0.4σ and 0.3σ with the latest values available in the literature. The estimated proper motion of the three T type dwarfs analyzed are at 7.7σ, 6.5σ and 1.9σ, respectively from the proper motion of the central multiple star σ Ori (Perryman et al. 1997). In the case of S Ori 70 and S Ori 73, these large differences are difficult to reconcile with the nearly null proper motion of the σ Orionis cluster. The estimated proper motion value of J0538−0213 is consistent with a null motion and with the σ Orionis cluster proper motion.

Based on our photometric, spectroscopic and astrometric study, the mass function depicted for the σ Orionis cluster in Peña Ramírez et al. (2012) remains within the error bars addressed by the authors. The presented observations suggest that none of the three T dwarfs are likely σ Orionis members, and that either planetary-mass objects with masses be-

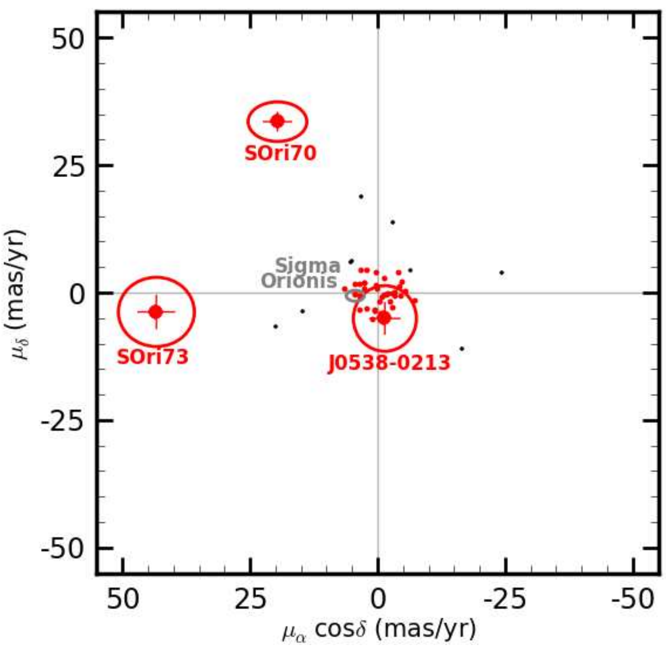

Figure .4: Proper motion diagram for S Ori 70, S Ori 73, and J0538−0213. The objects of interest are labelled. All the sources within the analyzed areas of each T type candidate image are plotted as small dots. The sources used as astrometric references are shown with red dots. The ellipses around S Ori 70, S Ori 73, and J0538−0213 represent their 2σ proper motion uncertainties. The *Hipparcos* motion of the σ Orionis cluster is depicted with a grey solid-line ellipse.

Table .1: LIRIS H band, methane photometry, proper motion measurements and spectral type estimations for the known T type sources towards the σ Orionis cluster.

Object	H (mag)	$H - CH_{4on}$ (mag)	Δt (yr)	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	P.A. (deg)	SpT (Spectra)
S Ori 70	20.065 ± 0.076	-0.604 $\pm$ 0.159	8.68	19.8 $\pm$ 2.9	33.7 $\pm$ 1.9	30.5 $\pm$ 2.1	T7$^{+0.5}_{-1.0}$
S Ori 73	20.580 ± 0.050[1]	-0.113 $\pm$ 0.146	8.82	43.6 $\pm$ 3.7	-3.6 $\pm$ 3.4	94.7 $\pm$ 4.5	T4.5$\pm$0.5
J0538−0213	19.241 ± 0.186[2]	-0.279 $\pm$ 0.212	7.03	-1.2 $\pm$ 3.1	-4.8 $\pm$ 3.2	14.0 $\pm$ 13.7	T5$\pm$0.5

(1) Adopted H–band value from Peña Ramírez et al. (2011). (2) Adopted H–band value from Peña Ramírez et al. (2012). In this case, the limiting magnitude of our LIRIS image is >18.7 mag.

low ~4 M_{Jup} may not exist free-floating in the cluster or they may lie at fainter near-infrared magnitudes than those of the targets, thus remaining unidentified.

Acknowledgements. We thank Philip Lucas for providing HST data. This work is based on observations made with the WHT, installed at the Spanish Observatorio del Roque de los Muchachos in the island of La Palma, Spain. Also based on observations made with ESO Telescopes at the Paranal Observatory under program ID 090.C-0766 and on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. This work is partly funded by the Spanish Ministry of Economy and Competitivity through the project AYA2011-30147-C03-03, AYA2010-20535 and the Chilean FONDECYT Postdoctoral grant 3140351.

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The closing reception was a BBQ atop Mars Hill, with the dome of the Pluto discovery telescope is in the background.