A&A 420, 283–287 (2004)
DOI: 10.1051/0004-6361:20034118

Astronomy & Astrophysics

Research Note

9+ frequencies for V534 Tauri, a δ Scuti variable in the Pleiades

Results of the STEPHI IX campaign★

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Received 25 July 2003 / Accepted 8 March 2004

Abstract. New observations of V534 Tau were performed during the STEPHI IX campaign in November 1998. An overall run of 285 h of data has been collected from three sites over a period of 23 days. Period analysis reveals a rich oscillation spectrum with nine frequencies above the 99% confidence level. This oscillation spectrum spans a large range of frequencies, from 179 to 525 μHz (15.52 to 45.36 cycles per day). A preliminary comparison with models suggests that the observed modes would lie in the range of modes from g_1 or g_2 to p_4 or p_5, depending on the rotation rate considered for V534 Tau.

Key words. galaxy: open clusters and associations: general – stars: variables: δ sct – stars: oscillations – stars: individuals: V534 Tau

1. Introduction

The data presented here are part of the programme initiated by the STEPHI network on δ Scuti stars in open clusters (see Michel et al. 2000). This programme has been motivated by the fact that for modeling and seismic interpretation it is an advantage if the target stars are cluster members. Some of these advantages have been illustrated by Michel et al. (1999), who proposed a method to estimate and take into account the effect of fast rotation on the determination of global parameters for rapidly rotating stars in clusters. This method, upgraded by Pérez Hernández et al. (1999), has opened up new perspectives for seismic investigation of these objects (e.g., Michel et al. 1999; Suárez et al. 2002).

In this paper, we present an analysis of the STEPHI IX campaign dedicated to the δ Scuti star V534 Tau in the Pleiades.

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★ Table 1 is only available in electronic form at http://www.edpsciences.org

2. The target stars: V534 Tau

V534 Tau (HD 23567) is a member of the Pleiades with spectral class A9 V, m_v = 8.4 mag and $v \sin i$ = 90 km s^{-1} (see Rodríguez et al. 2000, and references therein). Its *uvbyβ* indices following Crawford & Perry (1976) are $b - y = 0.229$, m_1 = 0.173, c_1 = 0.748, β = 2.788. Using the calibration derived by Crawford (1979) for M_v and by Moon & Dworetsky (1985) for the effective temperature and gravity, we obtain M_v = 2.87 mag, $T_{\rm eff}$ = 7700 K and log g = 4.30. This estimate of the absolute magnitude is in agreement with the distance modulus obtained for the Pleiades (5.37 mag) by van Leeuwen (1999) with Hipparcos data. According to these values, V534 Tau is located on the main sequence, near the red edge of the instability strip.

HD 23567 was found to vary during a systematic search for variability in the Pleiades (Breger 1972). Its period was estimated to be 0.032 ± 0.004 days, with an amplitude ranging between 0.01 and 0.02 mag. Strong changes in the amplitudes were found in the 11 h run, suggesting a rich oscillation spectrum.

We selected V534 Tau as main target for the November 1998 multisite campaign of the STEPHI network.

3. The observations

The STEPHI-98 campaign was held in November 1998, with the participation of the three observing sites regularly involved in STEPHI: Observatorio de San Pedro Martir (SPM, operated by UNAM), Baja California, Mexico; Xing Long station (XL, operated by the Beijing Observatory), Heibe province, China; and Observatorio del Teide (OT, operated by the IAC), Tenerife, Spain. Altogether, forty individual runs were obtained over the period November 7–30 (see Table 1), yielding about 285 h of usable data over this period, i.e. an effective observational coverage of around 52% (about 75% of the telescope time attributed!).

The observational procedures at SPM and OT were the same as in the other STEPHI campaigns. Four-channel photometers (Michel et al. 1995) were used at both sites. Three of the channels were used to monitor the stars (main target, first comparison star and supplementary star), while the fourth channel was devoted to measuring the adjacent sky brightness. Interferometric blue filters ($\lambda \sim 4100$ Å, $\Delta\lambda \sim 190$ Å) were used in each channel.

At Xing Long station, two-colour observations were obtained to test the potential help this could bring to mode identification. The multichannel photometer has thus been adapted, as noted by Li et al. (2000), allowing the monitoring in Strömgren v and y, but for two objects and sky background only. Unfortunately, the y band does not provide good enough data to aid frequency analysis and mode identification significantly. These data will be omitted in this report.

At SPM, HD 23568 (B9.5 V, $m_v = 6.80$ mag) and HD 23627 (B8, $m_v = 8.73$ mag) have been used as comparison stars.

At OT, HD 23628 (A4 IV, $m_v = 7.68$ mag) and HD 23627 have been selected as comparison stars, and at XL, HD 23628 was the only comparison star.

During this campaign, HD 23628 has been discovered to be a δ Scuti star showing very low amplitude oscillations (Li et al. 2002). This fortunate discovery had to be taken into account in the data analysis, as explained in Sect. 4.

4. Data reduction and analysis

The data were reduced following the classical data reduction scheme for multichannel rapid photometry (see for instance Hernández et al. 1998). The time series corresponding to the sky background contribution was first subtracted from the time series associated with the channels dedicated to different stars. This was done taking into account sensitivity ratios between different channels. These sensitivity ratios are estimated from sky-flat sequences, one at the beginning of the night and one at the end, when all the different channels are observing the twilight sky simultaneously. The sensitivity ratio at a given time is obtained by a linear interpolation in time between these two values. The time series thus obtained for V534 Tau is then divided by that obtained for the comparison and supplementary star in order to correct for extinction effects.

The long-term stability of our measurements is not guaranteed against slow relative drifts in the sensitivity of the photomultipliers of the different channels, and we thus do not aim to address the low frequency domain (periods longer than a couple of hours). In addition to this, to do the analysis we had to merge time series obtained at different sites with different comparison stars. We thus normalized the time series by subtracting from each differential light curve a low degree ($\leq$2) polynomial fit. The time was converted to Heliocentric Julian Date and resampled with a 1 min average. After this correction, we found that data from different sites overlapping in time converged very satisfactorily (Fig. 4).

To disentangle contributions of different objects and confirm which frequencies can be safely attributed to V534 Tau, we made use of the following three time series in the analysis.

TS1 results from the merging of the differential time series for three sites: V534 Tau/HD 23628 (for XL) + V534 Tau/HD 23627 (for OT and SPM). This is our most extended time series, associated with a very good observational window. It thus provided the best quantitative determination of the V534 Tau oscillation spectrum. The oscillation frequencies attributed to HD 23628 (Li et al. 2002) were pre-whitened from the XL time series before merging.

TS2 is exactly the same as TS1 but excluding the XL contribution. This time series thus results from the merging of the data from two sites only and cannot be expected to proved results as good as those for TS1 in terms of the observational window, but we used it to demonstrate that all the peaks detected in the TS1 analysis are also present in TS2 and thus validate the fact that the use of HD 23628 as a comparison for XL in TS1 does not cast any doubt on the results.

TS3 is composed of the merging of V534 Tau/HD 23628 (XL + OT). This time series was used to demonstrate that the frequencies detected in TS1 and TS2 are present in TS3 and thus cannot be attributed to HD 23627.

The analysis was carried out as described in Li et al. (1991), using the program period98 (Sperl 1998).

The analysis of TS1 is illustrated in Fig. 1. The Fourier transform of the observational window is shown at the top of the figure. The 1 cycle per day first alias is only 0.4 times (in amplitude) the main peak thanks to the observational coverage from three sites. Figure 1 also shows the amplitude spectra of the data before and after subtraction of the nine-frequency solution.

The amplitude-to-noise ratios corresponding to these nine peaks are found to lie between 4.2 and 13.5 (Table 2) corresponding to a detection confidence level higher than 99% following Fisher's test (see Nowroozi 1967). The mean noise level considered as a reference in Table 2 was estimated as a function of frequency after subtraction of the six highest peaks detected.

After removal of the nine previous frequencies, a few additional peaks were found with an *S/N* ratio between 3.5 and 3.9. They are given here for reference: 8.99, 12.07, 19.57, 27.89 and 37.11 cycles per day.

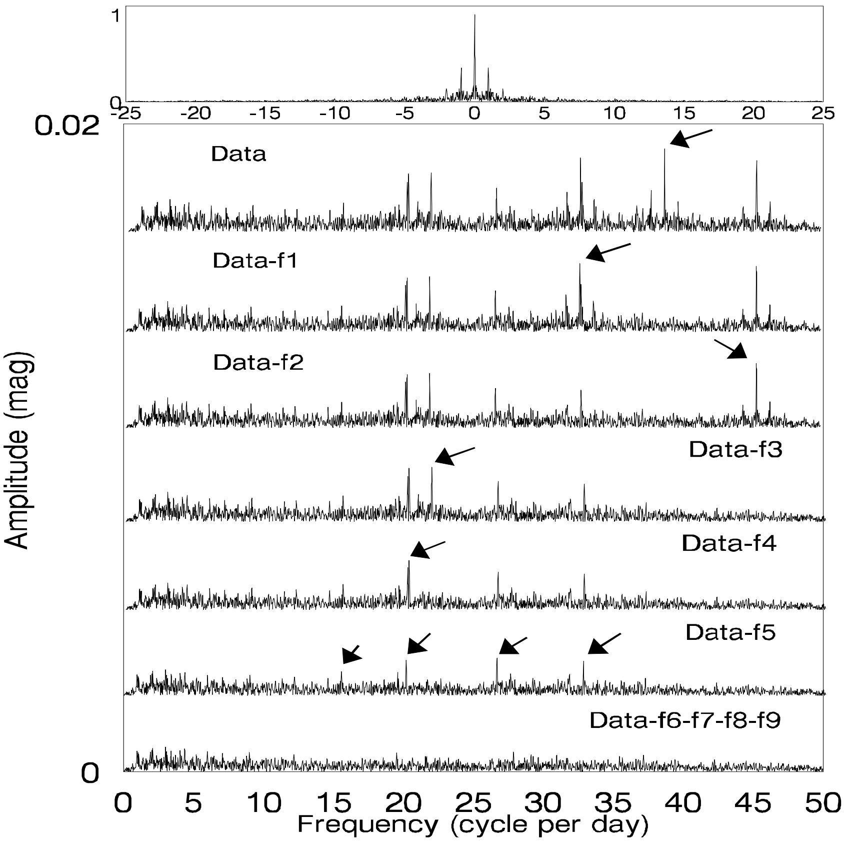

Fig. 1. The amplitude spectra for the TS1 time series. The spectra are shown before and after subtracting different peaks.

Table 2. The frequency spectrum of V534 Tau.

Name	Frequency c d^{-1}	μHz/ID	Amplitude v filter mmag	Significance ampltude *S/N*
f_1	38.7140732	448.09	2.09	12.4
f_2	32.6473815	377.88	1.71	10.1
f_3	45.3560617	524.97	1.76	13.5
f_4	21.8546593	252.96	1.50	8.0
f_5	20.2262439	234.11	1.34	7.5
f_6	26.5825568	307.68	1.11	6.5
f_7	32.7485953	379.05	1.08	6.5
f_8	20.1277342	232.97	1.07	5.9
f_9	15.5210240	179.65	0.75	4.2

A similar analysis of TS2 time series is illustrated in Fig. 2. All the peaks found in the analysis of TS1 and given in Table 2 were found, except the peak at frequency 32.65 c/d which turned into 31.65 c/d. This is interpreted as a 1 c/d alias misidentification due to the fact that the observational window associated with TS2 is not as good as the one associated with TS1. We thus conclude that none of these frequencies can be attributed to HD 23628.

The analysis of the TS3 time series confirms that the peaks found in TS1 and TS2 are present in TS3 and thus cannot be attributed to HD 23627 (see Fig. 3).

In Table 2, we summarize the characteristics of the nine oscillation frequencies attributed to V534 Tau. The fit to the data is shown in Fig. 4.

5. Preliminary comparison with models

The present analysis confirms that V534 Tau has a rich oscillation spectrum spanning a large frequency range.

Detailed modelling of this star is beyond the scope of the present paper and will be addressed in a dedicated article. Here, we simply propose a comparison with representative models to produce an indicative estimate of the radial order of the detected eigenfrequencies.

Suarez et al. (2002) derived an estimate for the global parameters of V534 Tau, taking into account the effect of its fast rotation. Following Suarez et al. (2002), we computed with the CESAM code (Morel 1997) a mass of 1.5 $M_{\odot}$, an age of 130 My, slightly sub-solar initial metallicity ([Fe/H] = -0.112, Grenon 2000) and rigid rotation at 95% of its break-up value (for further details on the physical options, see Suárez et al. 2002).

For this model, we computed the oscillation eigenfrequencies with the Filou code (Tran Minh & Leon 1995), including the perturbative treatment of rotation up to second order, as described in Soufi et al. (1998). According to these results, the observed lowest frequency, f_9, would lie in the domain of the first g-modes (g_1 or g_2) below the fundamental radial, while the remaining observed frequencies would span the range of frequency from the fundamental radial mode up to the fifth overtone (p_5).

We notice that reducing drastically the rotation rate (to zero rotation), or slightly changing the initial metallicity (up to solar), does not change the result of this comparison by much

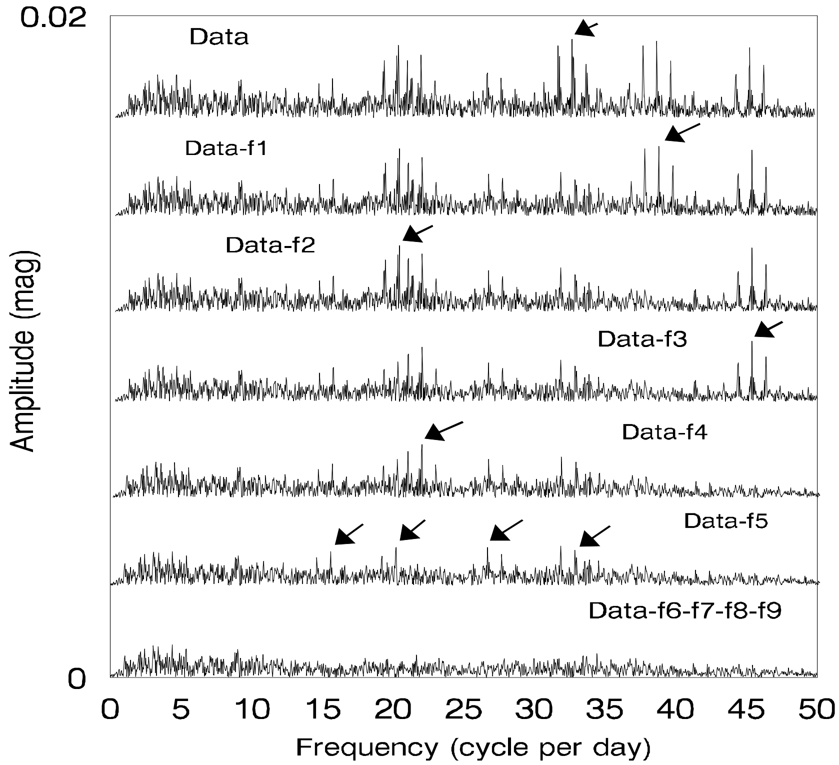

Fig. 2. Same as Fig. 1, but for the time series TS2.

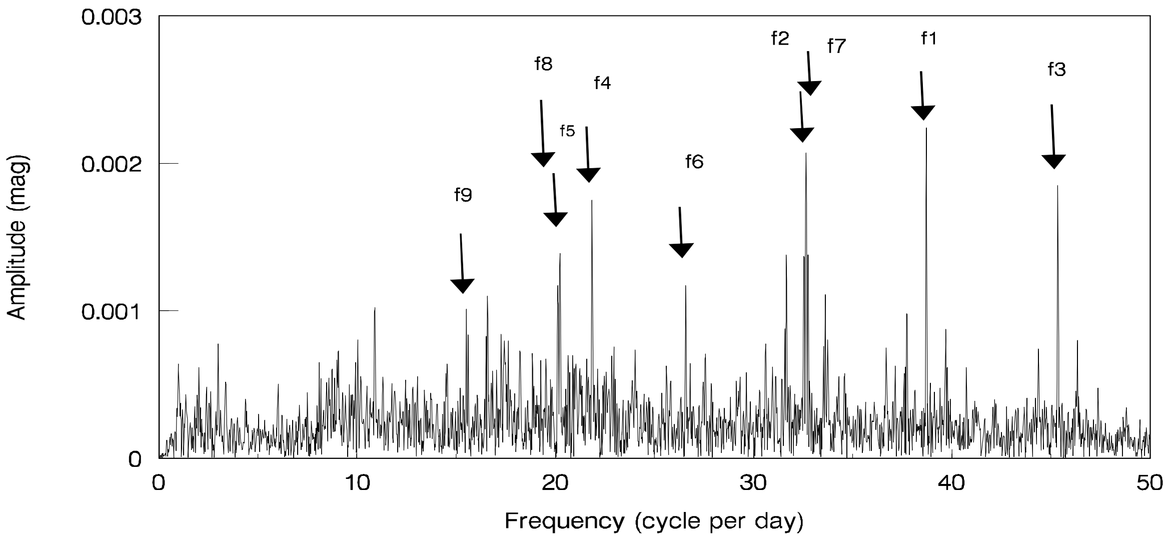

Fig. 3. The amplitude spectrum of V534 Tauri for the time series TS3. All nine frequencies identified in the time series TS1 have corresponding frequency peaks in this spectrum.

(g_1 or g_2 still, to p_4 instead of p_5). We also note that f_9, with the lowest signal-to-noise ratio, is the only frequency peak that lies necessarily (with these models) in the g-mode range.

6. Conclusion

We present the analysis of the STEPHI-98 (STEPHI IX) multisite campaign dedicated to the Delta Scuti star V534 Tau. About 285 h of photometry data have been obtained from three sites over a period of 23 days. The noise level is about 2×10^{-4} mag in amplitude over the range of frequencies of interest here. The spectral window is very satisfactory with the first 1 c/d side lobes at 40% of the main lobe in amplitude.

Nine frequencies are detected with a confidence level higher than 99%. These oscillation frequencies span a large range (345 μHz).

A preliminary comparison with models suggests that the observed modes would lie in the range from the first g-modes below the fundamental mode up to the fourth or fifth overtone.

Acknowledgements. The STEPHI program has received financial support from the French CNRS, the Chinese National Natural Science

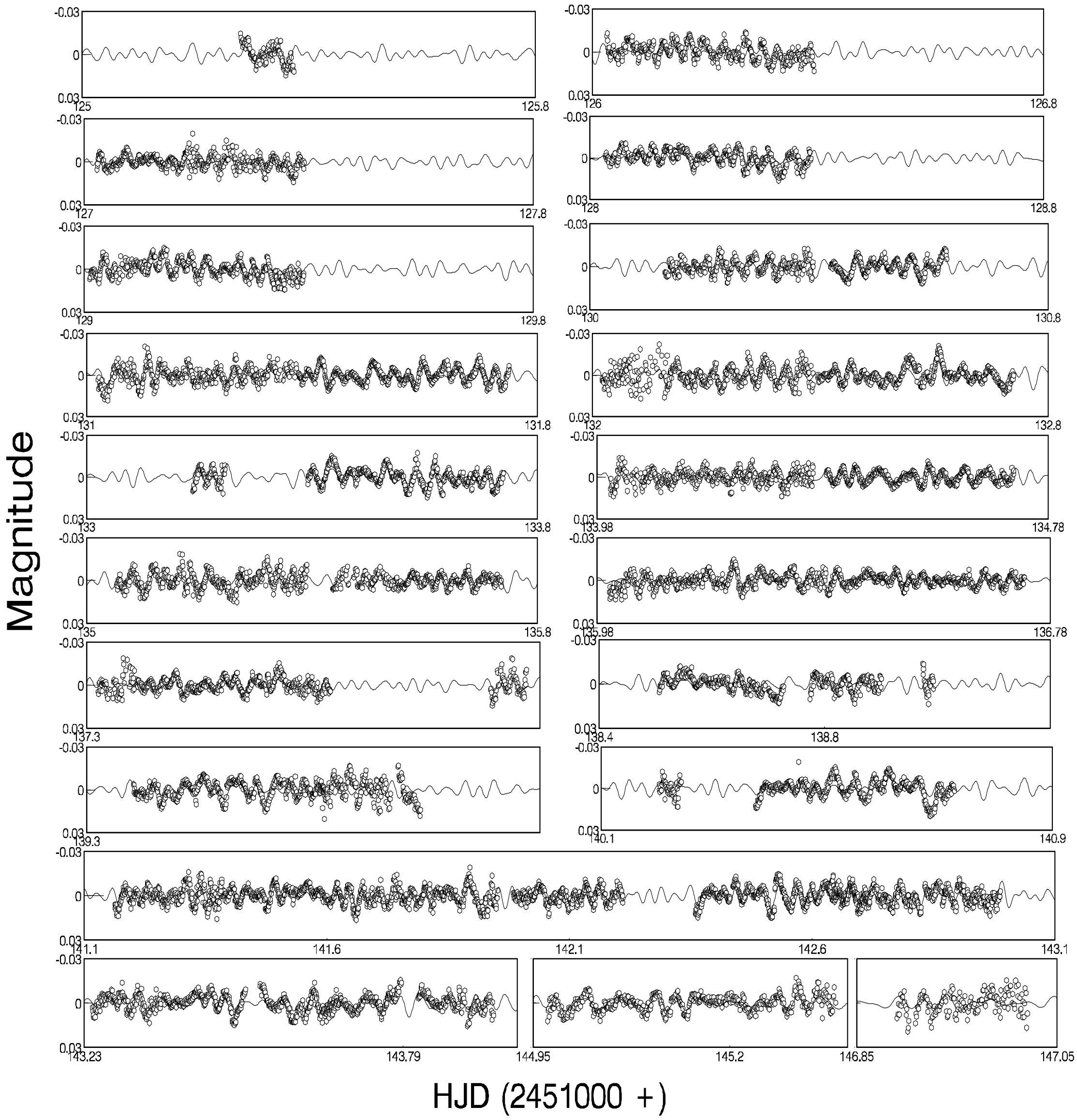

Fig. 4. The fit of the nine-frequency solution to the data observed on November 7–30 at three sites.

Foundation and Academia Sinica, the Spanish DGICYT, and the Mexican CONACYT and UNAM. Special thanks are given to the staff of the observatories involved in the campaign. The STEPHI team would like to express its deep sorrow at the death of Bernard Servan and dedicate this campaign to him.

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Online Material

Table 1. Log of the observations of V534 Tau.

Day	Date 1998	Observatory	Start time (HJD)	End time (HJD)
1	Nov. 07–08	Xing Long Station	125.19	125.41
2	Nov. 08–09	Xing Long Station	126.02	126.40
3	Nov. 09–10	Xing Long Station	127.02	127.40
4	Nov. 10–11	Xing Long Station	128.02	128.38
5	Nov. 11–12	Xing Long Station	129.00	129.39
6	Nov. 12–13	Xing Long Station	130.13	130.38
7	Nov. 12–13	Teide Observatory in Tenerife	130.42	130.63
8	Nov. 13–14	Xing Long Station	131.02	131.38
9	Nov. 13–14	Teide Observatory in Tenerife	131.37	131.75
10	Nov. 14–15	Xing Long Station	132.01	132.39
11	Nov. 14–15	Teide Observatory in Tenerife	132.39	132.74
12	Nov. 15–15	Xing Long Station	133.18	133.26
13	Nov. 15–16	Teide Observatory in Tenerife	133.39	133.94
14	Nov. 16–17	Xing Long Station	134.00	134.37
15	Nov. 16–17	Teide Observatory in Tenerife	134.38	134.72
16	Nov. 17–18	Xing Long Station	135.05	135.40
17	Nov. 17–18	Teide Observatory in Tenerife	135.43	135.74
18	Nov. 18–19	Xing Long Station	136.00	136.39
19	Nov. 18–19	Teide Observatory in Tenerife	136.38	136.74
20	Nov. 19–20	Xing Long Station	137.32	137.39
21	Nov. 19–20	Teide Observatory in Tenerife	137.38	137.74
22	Nov. 20–21	Xing Long Station	138.01	138.09
23	Nov. 20–21	Teide Observatory in Tenerife	138.50	138.73
24	Nov. 21–22	San Pedro Martir Observatory	138.77	139.02
25	Nov. 21–22	Teide Observatory in Tenerife	139.38	139.73
26	Nov. 22–23	San Pedro Martir Observatory	139.69	139.99
27	Nov. 22–23	Xing Long Station	140.20	140.25
28	Nov. 22–23	Teide Observatory in Tenerife	140.37	140.73
29	Nov. 23–24	Xing Long Station	141.16	141.39
30	Nov. 23–24	Teide Observatory in Tenerife	141.35	141.72
31	Nov. 24–25	San Pedro Martir Observatory	141.72	141.96
32	Nov. 24–25	Xing Long Station	141.98	142.22
33	Nov. 24–25	Teide Observatory in Tenerife	142.35	142.72
34	Nov. 25–26	San Pedro Martir Observatory	142.63	143.00
35	Nov. 25–26	Xing Long Station	143.24	143.37
36	Nov. 25–26	Teide Observatory in Tenerife	143.36	143.68
37	Nov. 26–27	San Pedro Martir Observatory	143.65	143.95
38	Nov. 26–27	Xing Long Station	144.27	144.38
39	Nov. 27–28	Xing Long Station	144.96	145.34
40	Nov. 29–30	San Pedro Martir Observatory	146.87	147.03