A&A 422, 505–508 (2004)
DOI: 10.1051/0004-6361:20040306

Astronomy & Astrophysics

Research Note

Near infrared intraday variability of Mrk 421⋆

A. C. Gupta[1], D. P. K. Banerjee[2], N. M. Ashok[2], and U. C. Joshi[2]

[1] Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 211 019, India
e-mail: agupta@mri.ernet.in
[2] Astronomy and Astrophysics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
e-mail: [orion;ashok;joshi]@prl.ernet.in

Received 20 February 2004 / Accepted 2 April 2004

Abstract. We report results from our monitoring of the BL Lac object Mrk 421 in the near-IR *J* band. The observations, aimed at studying the intraday variability (IDV) of the object, were carried out systematically over an extended (and near-continuous) period of eight nights from the 1.2 m Mount Abu Infrared Telescope, India. There are limited studies for Mrk 421 in the *J* band for such an extended period. The observation epoch for this study (25 February–5 March 2003) was chosen to significantly overlap other concurrent studies of Mrk 421 in the X-ray/γ-ray regions being conducted using the Rossi X-ray timing explorer (RXTE) and the solar tower atmospheric Cherenkov effect experiment (STACEE). Hence these results could be useful for a multi-wavelength analysis of the variability behavior of Mrk 421. We find that Mrk 421 was quite active during the observed period and showed significant IDV and short term variability. A maximum variation of 0.89 mag is seen over the entirety of the observed period. Flaring activity, with typical brightness variations of ~0.4, are also seen on several occasions. The extent of the variability observed by us is compared with the results of other similar studies of Mrk 421 in the *J* band.

Key words. BL Lacertae objects: individual: Mrk 421 – BL Lacertae objects: general – infrared: general

1. Introduction

In this work we report our studies of the BL Lac object Mrk 421. BL Lac objects are a class of radio-loud active galactic nuclei (AGNs) and a subclass of blazars. They often show large and violent variations in the complete electromagnetic spectrum and their emission is strongly polarized. Their radiation at all wavelengths is predominantly nonthermal. Compared to radio frequencies, more rapid changes are seen to occur at optical and near-IR bands (Stein et al. 1976). Using an orientation-based unification scheme for radio-loud AGNs, a BL Lac object is considered to manifest itself when the relativistic jets emerging from the very core of the galaxy are pointing nearly towards the observer (Urry & Padovani 1995).

In general the spectral energy distribution (SED) of blazars has two components. The first component peaks in the IR-to-optical region for the so called red blazars (or low energy blazars – LBL) while it peaks in the UV/X-ray region for the blue blazars (or high energy blazars – HBL) (Padovani & Giommi 1995). The origin of the first component is attributed to synchrotron emission from high energy electrons in the relativistic jet. The second component, which extends up to γ-rays, peaks at GeV energies in LBLs and at TeV energies in HBLs. The high energy peak is generally attributed to Inverse Compton (IC) scattering of soft photons. However, the origin of the soft photons that seed the IC component of blazar spectrum is not a well understood aspect in the study of blazars.

Mrk 421 was first noted to be an object with a blue excess which turned out to be an elliptical galaxy with a bright, point like nucleus (Ulrich et al. 1975). The object showed optical polarization and the spectrum of the nucleus was seen to be featureless – an aspect common to BL Lac objects. It is a nearby BL Lac object (z = 0.031) which is classified as an HBL source because the energy of the synchrotron peak in its SED is higher than 0.1 keV. It is the brightest BL Lac object at X-ray and UV wavelengths. Mrk 421 was the first extragalactic source discovered at TeV energies at the 6 σ level by the Whipple group (Punch et al. 1992) which was confirmed by the high energy gamma ray astronomy (HEGRA) group (Petry et al. 1996). It is the first AGN detected by STACEE in the 140 GeV band (Boone et al. 2002). It is one of the AGNs detected by the energetic gamma ray experiment telescope (EGRET) instrument in the 30 MeV–30 GeV energy range by the Compton gamma ray observatory (CGRO) (Thompson et al. 1995). The imaging Compton telescope (COMPTEL) has also detected Mrk 421 in the 10–30 MeV range at the 3.2 σ level (Collmar et al. 1999).

Blazar variability can be broadly divided into 3 classes viz. microvariability or intra-day variability (IDV), short term outbursts and long term trends. Significant variations in flux of

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

a few tenths of a magnitude over the course of a day or less is often known as microvariability. Short term outbursts can range from weeks to months and long term trends can have time scales of several years. The first convincing evidence of optical IDV was found in the blazar BL Lacertae (Miller et al. 1989). Specifically, Mrk 421 has been studied for variability in all regimes of the electromagnetic spectrum. Large and fast variations are often found in the optical – e.g. a large optical variation of 4.6 mag has been seen in Mrk 421 (Stein et al. 1976) and rapid optical variability is well exemplified by the detection of a 1.4 mag brightness change in the object in a 2.5 h period (Xie et al. 1988). In the near-IR – the region with which we are concerned here- there have also been efforts to monitor variability in Mrk 421. An exhaustive compilation summarizing all the near-IR results of Mrk 421 stretching over three decades is given in the recent work by Fan & Lin (1999). From this work, and also subsequent reports, we note that there have been very few studies of micro and short-term variability of Mrk 421 in the J band. The notable studies in this respect are those by Takalo et al. (1992), Makino et al. (1987) and Kidger et al. (1999). The study by Takalo et al. (1992) gives short-term variability in 2 nearby slots (JD 2 448 272–2 448 280 and 2 448 324–2 448 335) with durations of 9 days and 12 days respectively. However their data gives one J magnitude per night and the sampling is generally over alternate nights – a total of 12 J magnitudes are reported. Makino et al.'s (1987) results constitute a part of an extensive multi-wavelength campaign. However we concern ourselves here with only their J band results which give single point data per night for 5 continuous nights. Kidger et al. (1999) have studied IDV over a period of 3 h in one night. Thus there is limited work which studies both IDV and short term variability in the near-IR bands with a good sampling rate. In view of this we decided to pursue the present study which addresses both the IDV and short term variability of Mrk 421. In addition to the above motivation, we were also made aware (Bhat 2003) that a multi-wavelength campaign using RXTE and STACEE was to be conducted for Mrk 421. We therefore have synchronized most of our observations with as many observation slots of the RXTE schedule as was possible. Hence the present J band data give simultaneous information in an additional spectral window. These observations should therefore make it possible to search for correlations and time delays between different spectral regions. Thus the present work could give useful input to multi-wavelength modeling of the Blazar phenomenon aimed at understanding the causes for their variability.

2. Observations and data reduction

Photometry in the J band was done at the Mt. Abu 1.2 m telescope using a Near Infrared Imager/Spectrometer with a 256×256 HgCdTe NICMOS 3 array. The instrument was used in the imaging mode with a $\sim 2 \times 2$ arcmin^2 field. Mrk 421 was observed continuously on all nights between 25 February and 5 March 2003 except on March 01, 2003 when unfavorable sky conditions did not permit observations. The sky was photometric during all epochs of observations. It would have been preferable if the object, standard and comparison stars were all present in the same image frame – this would have minimised the errors caused by sky transparency and seeing on the derived magnitudes of Mrk 421. Since there are no bright stars in the $\sim 2 \times 2$ arcmin^2 Mrk 421 field that can serve this purpose, we have chosen very nearby standard and comparison stars to circumvent this problem. The UKIRT standard star HD 105601 ($J = 6.821$) was used for photometric calibration for all observations. Also, as a reliability check for any observed variations in Mrk 421, the comparison star HD 95884 was observed. Mrk 421, HD 105601 and HD 95884 were all observed at similar airmass to minimize atmospheric extinction corrections in their derived magnitudes. Observations of the comparison and standard stars were done just before or immediately after the observations of Mrk 421. The standard and comparison stars were observed once during the course of the night on four epochs viz. 25, 26, 27 February and 4 March, twice during 2, 3 and 5 March and thrice on 28 February. The sequence of observations, for each of the standard/comparison stars and Mrk 421, involved the following procedure. Several images were obtained, in at least four dithered positions, offset by approximately 30 arcsec. The dithered frames were median-combined (using IRAF) to generate the corresponding sky frame which was then subtracted from the object frames. Aperture photometry was done at each dithered position using the APPHOT task from IRAF to yield an instrumental magnitude. Since the observation cycle is small for the standard and comparison stars (both being bright), their derived magnitudes from the different dithered positions were averaged to yield a mean value. The aperture size, during aperture photometry, was chosen to be generally four times the FWHM of the recorded stellar image (i.e. typically 6–8 arcsec). The atmospheric correction for the instrumental magnitudes was done using an average extinction coefficient of $k_j = 0.15$ for the J band for the Mt. Abu Observatory site. A detailed log of the observations and the derived magnitudes for Mrk 421 is presented in Table 1. Similar details for the comparison star HD 95884 are given in Table 2.

Table 2. The log of observations for HD 95884 and its derived magnitudes. Some of the abbreviated titles are: exposure time is represented by Exp. time, Total integration time by Int. time, Air mass by A.M and J band magnitude by J mag., JD is measured from 2 450 000+.

JD	Exp. time(s)	Int. time(s)	A.M	Seeing ($''$)	J mag. (Error)
2696.410	0.4	3.6	1.049	1.7	6.75(0.02)
2697.304	2.0	8.0	1.039	1.6	6.67(0.05)
2698.278	2.0	8.0	1.060	1.6	6.67(0.04)
2699.229	2.0	18.0	1.172	1.8	6.67(0.06)
2699.277	2.0	18.0	1.061	1.6	6.69(0.05)
2699.290	2.0	18.0	1.045	1.7	6.71(0.06)
2701.288	2.0	18.0	1.044	1.9	6.62(0.12)
2701.338	2.0	18.0	1.040	1.7	6.71(0.16)
2702.297	2.0	18.0	1.035	1.9	6.76(0.09)
2702.351	2.0	18.0	1.055	1.8	6.75(0.07)
2703.272	2.0	18.0	1.053	1.5	6.64(0.15)
2704.377	2.0	10.0	1.111	1.3	6.77(0.02)
2704.419	2.0	10.0	1.253	1.5	6.75(0.01)

From Table 2 it is seen that the mean *J* magnitude of HD 95884 of 6.705 agrees well with its 2MASS magnitude of 6.693.

3. Results and discussion

We have shown in Fig. 1 the *J* band light curve of Mrk 421 on the individual nights of observation. The periods of overlap of our data with RXTE observations are also indicated. From our data it is seen that the maximum variation of the source is 0.89 mag (between its brightest level at 11.12 mag on JD 2 452 696.399 and faintest level at 12.01 mag on JD 2 452 698.260). In comparison, the data from Takalo et al. (1992) show a maximum change of 0.32 mag during their observations while the Makino et al. (1987) observations show a marginal change of only 0.03 mags. This shows that the source was quite active during our epoch of observations. In terms of flux variation, the observed 0.89 mag change corresponds to a large 84 percent peak-to-peak variation in the average *J* band brightness of Mrk 421 (the average *J* magnitude for the 95 observed data points is 11.559). It also appears that the faintest level of the source detected by us (12.01 mag) could might be possibly be the faintest recorded magnitude for this object (by comparing with data from Fan & Lin 1999). The maximum brightness variation recorded on the individual nights (in sequence of observation date) are 0.15, 0.29, 0.34, 0.34, 0.59, 0.47, 0.49 and 0.39 mag respectively. Thus considerable IDV in Mrk 421 is seen on all nights. As a comparison we note that the observations of Kidger et al. (1999) over a 3 h period show a maximum variability of ~0.1 mag.

The short term variability is best seen from Fig. 2 where we have plotted average brightness values on the individual nights in the upper panel. The middle panel shows all the data of Fig. 1 in a more compact and comprehensive format to enable comparison with the upper panel. The lowest panel of Fig. 2, which shows the near-constancy of the observed magnitudes for the comparison star HD 95884, can be used to judge the validity of the observed variability in Mrk 421. Figure 2 (top panel) shows that there are short term variations during 25–28 February, a near constant phase between 2–4 March followed by a slight decline on 5 March. Some amount of flaring activity is seen in Mrk 421. On 2 March a flare is seen at JD 2 452 701.317, with a brightness excursion of 0.48 magnitudes. Similarly a flare is seen on 3 March and two flares on 4 March at JD 2 452 702.341, JD 2 452 703.316 and JD 2 452 703.367 with variations of 0.45, 0.29 and 0.49 magnitudes respectively. Further, the data of Feb. 25 suggest that a flare could have just preceded our first data point on that date since the source was seen to be brightening and reached its brightest level on that date. It may be mentioned that Takalo et al. (1992) have also detected two instances of flares in Mrk 421 with *J* band variations of 0.25 and 0.2 mag.

It is useful to examine how the observed *J* magnitudes of Mrk 421 are affected by variations in the seeing conditions. A variation in seeing can lead to a change in the observed brightness of Mrk 421 because of differing brightness contributions – within a measuring aperture diameter – from the host galaxy that surrounds Mrk 421. A detailed study in this context has been done by Nilsson et al. (1999) in the *R* band for three

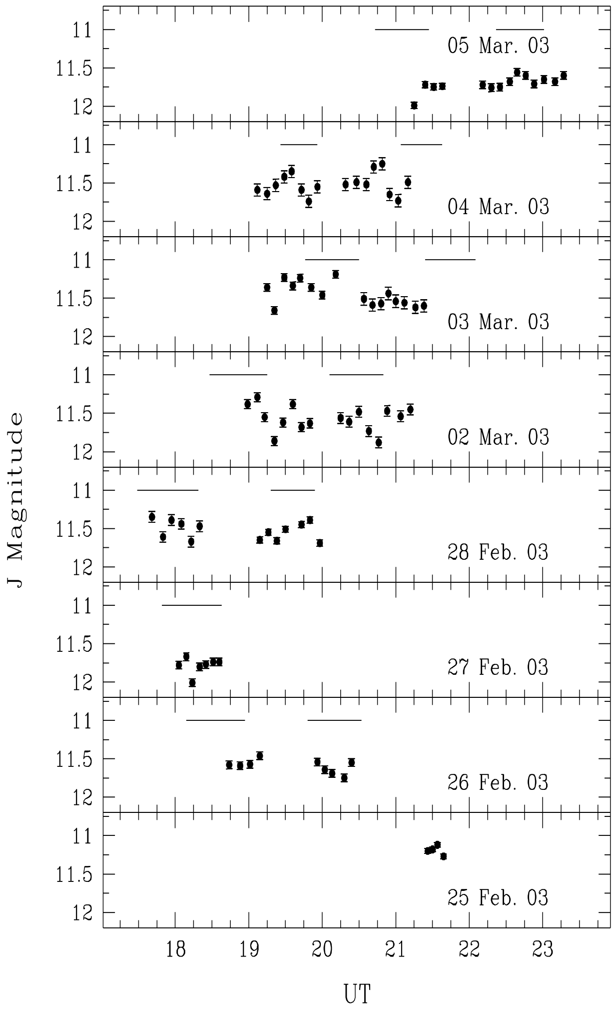

Fig. 1. The *J* band light curve of Mrk 421 during Feb. 25–March 05, 2003. Data for an individual night are plotted in one panel. We have also indicated, by horizontal lines, the periods for which there is a temporal overlap between the present data and the RXTE observation slots.

BL Lac objects including Mrk 421. While their *R* band results cannot be extrapolated directly to the *J* band observations reported here, it is still instructive to make an assessment of the effects of seeing on the *J* magnitudes reported here. From the compiled data of Nilsson et al. (1999; refer Table 6), by choosing an aperture diameter of 7.5″ – which is quite represenative of the aperture used in the present studies – it is seen that a variation in the seeing from 2″ to 4″ changes the relative contribution of the host galaxy to the observed *R* magnitude of Mrk 421 from 0.04 to 0.18 mag i.e. a change of 0.14 mag for a 2″ change in seeing. In this respect we have given the seeing value in arc seconds for the comparison star HD 95884 in Table 2. The seeing was estimated by measuring the full width at half maximum of the stellar images of this star. The seeing values during the Mrk 421 observations can be assumed to be similar to those of HD 95884 since observations of both objects were separated by small time differences and were also made at similar airmass. As may be seen from Table 2, the seeing values were fairly constant and did not vary significantly during the different epochs of Mrk 421 observation. Thus we would infer

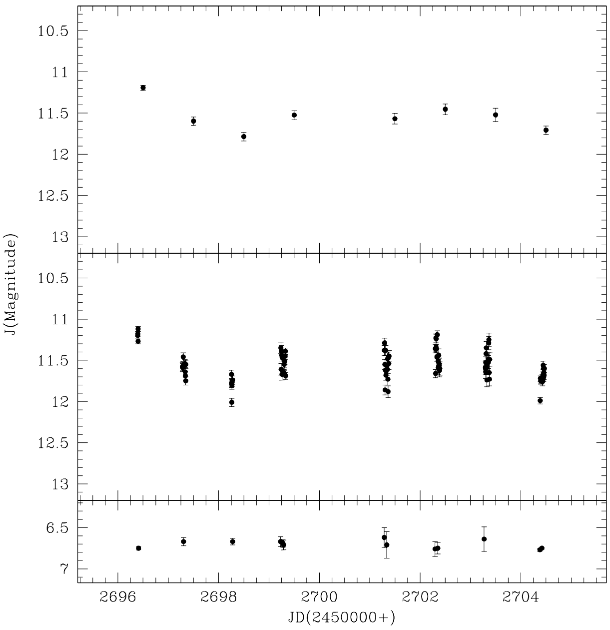

Fig. 2. The upper panel shows the mean J magnitude on 8 nights (between 25 Feb. to 5 March 2003) for Mrk 421. The middle panel of the above plot shows the complete set of data points of our observations. The lowest panel shows the mean J magnitudes for the comparison star HD 95884.

that the small, observed changes in the seeing could have only a marginal effect on the observed J magnitudes. The above arguments would therefore indicate that the observed short-term and intra-day variability in Mrk 421 – the central point of this study – that are reported here are reliable. It is however outside the scope of this work to construct two-dimensional photometric maps of Mrk 421 to "clean" the observed J band magnitudes of the host galaxy contribution as has been done in the detailed analysis by Nilsson et al. (1999).

From different multiwavelength campaigns it has been seen that strong optical variations are generally not seen during X-ray and γ-ray flaring events (Tosti et al. 1998 and references therein). However, there is some evidence that optical flares are generally accompanied by X-ray and γ-ray flares (Hartman et al. 2001). A similar correlated variability is also seen for the radio region. Katarzyński et al. (2003) shows a well defined correlation between observed radio outbursts in Mrk 421 with a corresponding X-ray outburst and a γ-ray flare in the TeV range. Since considerable flaring activity is seen in the present J band data, it will be interesting to see whether there is correlated variability in the X-ray/γ-ray regimes. RXTE and STACEE observations, which have been done simultaneously, can confirm this.

There are several models that explain the intraday and short term variability in blazars viz. shock-in-jet models, accretion-disk based models and plasma-process related models that can explain IDV over an extended range of wavelengths (Wagner & Witzel 1995; Urry & Padovani 1995, and references therein). The observed variability in our present data – taken by itself – could be consistently explained by any successful model for IDV. However, when taken in conjunction with X-ray/γ-ray data it may provide a more definite insight into the observed IDV in Mrk 421.

Acknowledgements. We thank the referee L. O. Takalo for constructive comments that have helped us to improve the paper. We are also grateful to P. N. Bhat, Tata Institute of Fundamental Research, Mumbai for bringing the RXTE observational campaign to our notice. The research work at Physical Research Laboratory is funded by the Department of Space, Government of India and at Harish-Chandra Research Institute by the Department of Atomic Energy, Government of India. IRAF is distributed by NOAO, USA.

References

Bhat, P. N. 2003, private communication
Boone, L. M., Hinton, J. A., Bramel, D., et al. 2002, ApJ, 579, L5
Collmar, W., Bennett, K., Bloemen, H., et al. 1999, ApL&C, 39, 57
Fan, J. H., & Lin, R. G. 1999, ApJS, 121, 131
Hartman, R. C., Villata, M., & Balonek, T. J. 2001, ApJ, 558, 583
Katarzyński, K., Sol, H., & Kus, A. 2003, A&A, 410, 101
Kidger, M. R., González-Pérez, & José, N. 1999, Astropart. Phys., 11, 201
Makino, F., Tanaka, Y., Matsuoka, M., et al. 1987, ApJ, 313, 662
Miller, H. R., Carini, M. T., & Goodrich, B. D. 1989, Nature, 337, 627
Nilsson, K., Pursimo, T., Takalo, L. O., et al. 1999, PASP, 111, 1223
Padovani, P., & Giommi, P. 1995, ApJ, 444, 567
Petry, D., Bradbury, S. M., Konopelko, A., et al. 1996, A&A, 311, L13
Punch, M., Akerlof, C. W., Cawley, M. F., et al. 1992, Nature, 358, 477
Stein, W. A., O'Dell, S. L., & Strittmatter, P. A. 1976, ARA&A, 14, 173
Takalo, L. O., Kidger, M. R., de Diego, J. A., et al. 1992, AJ, 104, 40
Thompson, D. J., Bertsch, D. L., Dingus, B. L., et al. 1995, ApJS, 101, 259
Tosti, G., Fiorucci, M., Luciani, M., et al. 1998, A&A, 339, 41
Ulrich, M. H., Kinman, T. D., Lynds, C. R., et al. 1975, ApJ, 198, 261
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wagner, S. J., & Witzel, A. 1995, ARA&A, 33, 163
Xie, G.-Z., Lu, R.-W., Zhou, Y., et al. 1988, A&AS, 72, 163

Online Material

Table 1. The log of observations for Mrk 421 and its derived magnitudes. Some of the abbreviated titles are: exposure time represented by Exp. time, Total integration time by Int. time and *J* band magnitude by *J* mag.

JD (2 450 000+)	Exp. time(s)	Int. time(s)	Airmass	*J* mag. (Error)	JD (2 450 000+)	Exp. time(s)	Int. time(s)	Airmass	*J* mag. (Error)
Feb. 25					2701.378	60	300	1.087	11.54(0.07)
2696.393	20	180	1.093	11.20(0.03)	2701.383	60	300	1.097	11.45(0.07)
2696.396	20	180	1.099	11.18(0.03)	**Mar. 03**				
2696.399	20	180	1.106	11.12(0.03)	2702.302	60	300	1.031	11.36(0.05)
2696.402	20	180	1.113	11.27(0.03)	2702.306	60	300	1.038	11.66(0.05)
Feb. 26					2702.312	60	300	1.029	11.23(0.05)
2697.281	60	540	1.065	11.58(0.05)	2702.317	60	300	1.029	11.34(0.05)
2697.287	60	240	1.055	11.59(0.05)	2702.321	60	300	1.030	11.24(0.05)
2697.292	60	240	1.047	11.57(0.05)	2702.327	60	300	1.031	11.36(0.05)
2697.298	60	240	1.042	11.46(0.05)	2702.333	60	300	1.034	11.46(0.05)
2697.331	60	240	1.029	11.54(0.05)	2702.341	60	300	1.040	11.19(0.05)
2697.335	60	240	1.030	11.64(0.05)	2702.357	60	300	1.057	11.51(0.08)
2697.339	60	240	1.031	11.69(0.05)	2702.362	60	300	1.063	11.59(0.08)
2697.346	60	240	1.034	11.75(0.05)	2702.367	60	300	1.070	11.57(0.08)
2697.350	60	240	1.037	11.55(0.05)	2702.371	60	300	1.078	11.44(0.08)
Feb. 27					2702.375	60	300	1.087	11.54(0.08)
2698.252	60	240	1.113	11.78(0.05)	2702.380	60	300	1.096	11.56(0.08)
2698.256	60	240	1.104	11.67(0.05)	2702.386	60	300	1.110	11.62(0.08)
2698.260	60	240	1.095	12.01(0.05)	2702.391	60	300	1.122	11.60(0.08)
2698.264	60	240	1.087	11.80(0.05)	**Mar. 04**				
2698.267	60	240	1.080	11.77(0.05)	2703.297	60	300	1.033	11.59(0.08)
2698.272	60	240	1.073	11.74(0.05)	2703.302	60	300	1.030	11.64(0.08)
2698.275	60	240	1.067	11.74(0.05)	2703.307	60	300	1.029	11.53(0.08)
Feb. 28					2703.312	60	300	1.029	11.42(0.08)
2699.237	60	300	1.149	11.35(0.07)	2703.316	60	300	1.029	11.35(0.08)
2699.243	60	300	1.132	11.61(0.07)	2703.322	60	300	1.030	11.59(0.08)
2699.248	60	300	1.118	11.39(0.07)	2703.326	60	300	1.032	11.74(0.08)
2699.253	60	300	1.106	11.44(0.07)	2703.331	60	300	1.035	11.55(0.08)
2699.259	60	300	1.092	11.67(0.07)	2703.347	60	300	1.048	11.52(0.08)
2699.264	60	300	1.083	11.47(0.07)	2703.353	60	300	1.055	11.49(0.08)
2699.298	60	300	1.038	11.65(0.04)	2703.358	60	300	1.062	11.52(0.08)
2699.303	60	300	1.035	11.55(0.04)	2703.363	60	300	1.069	11.29(0.08)
2699.308	60	300	1.033	11.66(0.04)	2703.367	60	300	1.077	11.25(0.08)
2699.313	60	300	1.031	11.51(0.04)	2703.372	60	300	1.085	11.65(0.08)
2699.322	60	300	1.029	11.45(0.04)	2703.376	60	300	1.095	11.73(0.08)
2699.326	60	300	1.029	11.39(0.04)	2703.382	60	300	1.107	11.49(0.08)
2699.332	60	300	1.030	11.69(0.04)	**Mar. 05**				
Mar. 02					2704.385	60	300	1.124	11.99(0.04)
2701.291	60	300	1.039	11.38(0.06)	2704.392	60	300	1.140	11.72(0.04)
2701.297	60	300	1.036	11.29(0.06)	2704.397	60	300	1.154	11.75(0.04)
2701.301	60	300	1.033	11.55(0.06)	2704.401	60	300	1.171	11.74(0.04)
2701.306	60	300	1.030	11.86(0.06)	2704.424	60	300	1.264	11.72(0.05)
2701.311	60	300	1.030	11.62(0.06)	2704.429	60	300	1.287	11.76(0.05)
2701.317	60	300	1.029	11.38(0.06)	2704.434	60	300	1.313	11.75(0.05)
2701.322	60	300	1.029	11.68(0.06)	2704.440	60	300	1.343	11.68(0.05)
2701.326	60	300	1.029	11.63(0.06)	2704.444	60	300	1.371	11.56(0.05)
2701.344	60	300	1.040	11.56(0.07)	2704.449	60	300	1.402	11.60(0.05)
2701.349	60	300	1.044	11.61(0.07)	2704.453	60	300	1.436	11.71(0.05)
2701.354	60	300	1.049	11.48(0.07)	2704.459	60	300	1.480	11.65(0.05)
2701.360	60	300	1.057	11.73(0.07)	2704.465	60	300	1.533	11.68(0.05)
2701.365	60	300	1.064	11.88(0.07)	2704.470	60	300	1.577	11.60(0.05)
2701.370	60	300	1.073	11.47(0.07)					