PASJ: Publ. Astron. Soc. Japan **60**, L37–L41, 2008 December 25

Detection of Polarimetric Variations Associated with the Shortest Time-Scale Variability in S5 0716+714

Mahito SASADA,[1] Makoto UEMURA,[2] Akira ARAI,[1] Yasushi FUKAZAWA,[1] Koji S. KAWABATA,[2] Takashi OHSUGI,[2] Takuya YAMASHITA,[2] Mizuki ISOGAI,[2] Shuji SATO,[3] and Masaru KINO[3]
[1]*Department of Physical Science, Hiroshima University, Kagamiyama 1-3-1, Higashi-Hiroshima 739-8526*
sasada@hep01.hepl.hiroshima-u.ac.jp
[2]*Astrophysical Science Center, Hiroshima University, Kagamiyama 1-3-1, Higashi-Hiroshima 739-8526*
[3]*Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602*

(Received 2008 July 19; accepted 2008 October 10)

Abstract

We present the results of near-infrared and optical observations of the BL Lac object S5 0716+714, carried out with the KANATA telescope. S5 0716+714 has both a long-term, high-amplitude variability and a short-term variability within one night. The shortest variability (microvariability) time-scale is important for understanding the geometry of jets and the magnetic field, because it provides a possible minimum size of variation sources. Here, we report on the detection of 15-min variability in S5 0716+714, which is one of the shortest time scales in optical and near-infrared variations observed in blazars. The detected microvariation had an amplitude of 0.061 ± 0.005 mag in the V band and a blue color of $\Delta(V-J) = -0.025 \pm 0.011$. Furthermore, we successfully detected an unprecedented, short time-scale polarimetric variation, which correlated with the brightness change. We revealed that the microvariation had a specific polarization component. The polarization degree of the variation component was higher than that of the total flux. These results suggest that the microvariability originated from a small and local region where the magnetic field was aligned.

Key words: BL Lacertae Objects: individual: S5 0716+714 — infrared: general — polarization

1. Introduction

Blazars are one class of active galactic nuclei (AGNs), whose relativistic jets are considered to be directed along the line of sight (Blandford & Königl, 1979; Antonucci et al. 1993). Blazars show a large and rapid variability, and their fluxes often vary by an order of magnitude on a time-scale of days. A short time-scale variability has also been reported, that is, a so-called intra-day variability or microvariability, having a time-scale of <1 d (e.g., Antonucci et al. 1993).

Observing the shortest time-scale variability gives important information for understanding the variation mechanism, the emitting region and the jet geometry. An extremely large variability with a time-scale of tens of minutes has recently been reported in the optical region (e.g., Xie et al. 2004 for eight blazars e.g., S5 0716+714). However, Cellone, Romero, and Araudo (2007a) argued that they can be spurious results due to systematic errors arising from analysis. The shortest time scale in blazar variability was, in general, believed to be several hours.

In the gamma-ray region, however, a significant variability with a time scale of minutes has recently been discovered by Albert et al. (2007) in Mrk 501 and Aharonian et al. (2007) in PKS2155−304. Also, in the optical band, a 15-min microvariation has been reported by Gupta et al. (2008) in Mrk 501. The amplitude of the microvariation was not so extremely large, but actually rather small, with 0.05 mag in the R band. Such a short time scale indicates that the size of the emitting region of the variation is smaller than the Schwarzschild radius, R_{S}, of the central black-hole in AGN if we assume typical values for the black hole mass and the jet Doppler factor. It is, hence, possible that microvariations originate from a small confined region, rather than the whole emitting area. On the other hand, the observational features of those shortest time scale variations have not been established due to a lack of detailed observations, for example, polarimetric and multi-wavelength observations.

The spectral energy distribution (SED) of blazars can be described by synchrotron radiation and inverse-Compton scattering. In the optical band, the synchrotron radiation is dominant. Variations of the polarization can, hence, be observed in blazars (e.g., Angel & Stockman 1980). Polarimetric observations provide an important clue concerning the magnetic field and its geometry. However, there have been few polarimetric observations of microvariability so far. Cellone et al. (2007b) observed hours-scale variations in the polarization of AO 0235+164. According to their observation, the temporal variation of the polarization parameters showed no correlation with the variation of the total flux. For the shortest time-scale variations (~ 10 min), there was no report on studying any possible correlation between the polarization and the total flux.

S5 0716+714 is a BL Lac object, and is one of the systems in which microvariability was observed. The variability was observed on time scales of days and hours (e.g., Wagner et al. 1996; Stalin et al. 2006 and Wu et al. 2007). Nilsson et al. (2008) estimated its redshift to be $z = 0.31 \pm 0.08$.

In order to study the mechanism of microvariability, and to find the shortest time scale variations, we performed photopolarimetric observations of S5 0716+714 in the optical and near-infrared (NIR) bands simultaneously. In this paper, we report on our detection of a 15-min variability with polarimetric variations. The 15-min variability has a small amplitude, but the light curve is very well-sampled. The paper is arranged as follows. In section 2, we present the observation method and analysis. In section 3, we report on the results of photometry and polarimetry. We discuss the emitting region and the geometry of the magnetic field based on the observations presented in section 4. Finally, our conclusion is stated in section 5.

2. Observation

In this paper, we focus on the observation on 2007 October 20. It was part of our monitoring this blazar in 2007 using TRISPEC attached to the 1.5-m "KANATA" telescope at Higashi-Hiroshima Observatory. TRISPEC has a CCD and two InSb arrays, producing photopolarimetric data in an optical band and two NIR bands simultaneously (Watanabe et al. 2005). The unit of the observing sequence consisted of successive exposures at four position angles of the half-wave plate: 0°, 45°, $22\overset{\circ}{.}5$, and $67\overset{\circ}{.}5$.

The integration times in each exposure were 63, 55, and 28 s for the V-, J-, and $K_{\rm S}$-band images, respectively. Our one polarimetric data was derived from each set of four exposures. Thus, the time resolution of our polarimetry was about 5 min, while that of our photometry was about 1 min. The sky condition was clear and stable during our observation. The full width at half maximum of the point spread function was typically $3''$. All images were bias-subtracted and flat-fielded, and then we performed aperture photometry with the *IRAF APPHOT* package. We adopted differential photometry with a comparison star taken in the same frame, and the aperture size was about $7''$. Its position was RA $= 07^{\rm h}21^{\rm m}52\overset{\rm s}{.}3$, Dec $= +71^\circ18'17\overset{''}{.}6$ (J2000.0), and the magnitudes were 12.48, 11.32, and 10.98 mag in the V, J, and $K_{\rm S}$ bands, respectively (González-Pérez et al. 2001; Skrutskie et al. 2006). We confirmed that the comparison star remained constant during the observation. The dispersion of the magnitudes of the comparison star was less than 0.005 mag, calculated with a check star at RA $= 07^{\rm h}21^{\rm m}54\overset{\rm s}{.}4$, Dec $= +71^\circ19'21\overset{''}{.}3$, which was also taken in the same frame of S5 0716+714; its magnitudes are 13.55 and 12.34 in the V and J bands. The comparison and check stars are listed in Ghisellini et al. (1997) as star B and C, respectively.

The instrumental polarization was confirmed to be smaller than 0.1% in the V band by observing unpolarized standard stars. We applied no correction. The zero point of the polarization angle was corrected as the standard system (measured from north to east) by observing the polarized stars. For the NIR bands, the polarimetric accuracy was worse ($> 0.4\%$), and we used the polarization parameter only in the V band in this paper.

3. Result

3.1. Photometric Observation

Raiteri et al. (2003) reported that the object is at about 13 mag and 15 mag in the V band in its bright and faint states, respectively, based on their 8-yr light curve from 1994 to 2002. In 2007 October, the object was in a bright state

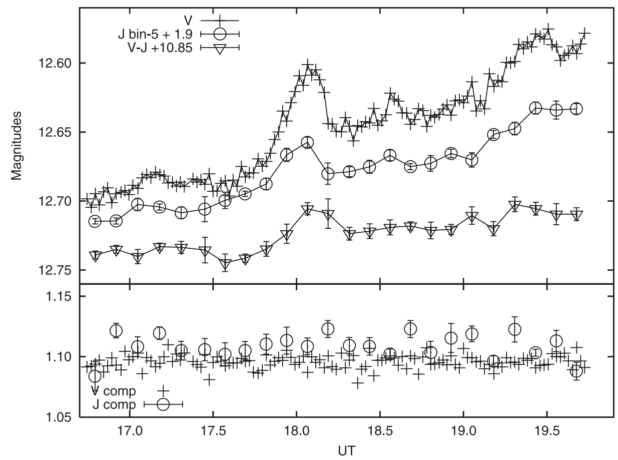

Fig. 1. Top panel: Light curves of the V, J bands and $V-J$ color on 2007 October 20. The time-bin sizes are 1- and 6-min in the V and J bands, respectively. Bottom panel: Differential magnitudes of the comparison star against the check star in the V and J bands, indicating that the magnitude of the comparison star was constant within 0.005 and 0.010 mag in the V and J bands, respectively.

at 12.6–13.5 mag. Figure 1 shows the light curves on 2007 October 20 when the object was the brightest in the period of our monitoring. During 3 hr of our observation on October 20, the object brightened by 0.123 ± 0.005 and 0.101 ± 0.010 mag in the V and J bands, respectively. In addition, there was a bump-like structure at around 18.0 (UT) on the overall brightening trend. The rising time of the bump was about 15-min in both the V and J bands. The amplitude of the bump was 0.061 ± 0.005 the and 0.035 ± 0.010 mag in the V and J bands, respectively. We did not consider the light curve in the $K_{\rm S}$ band, because the error of each photometric point was large, about 0.1 mag.

The time-scale, $\Delta\tau$, of the bump is estimated to be

$$\Delta\tau = \frac{1}{1+z}\frac{(\Delta F)}{dF/dt}, \tag{1}$$

where $1+z$ stands for a cosmological effect (Romero et al. 2002). The rising and decaying time-scales of the bump were 970 and 620 s in the observer frame. These values were estimated after the overall brightening trend was subtracted. With $z = 0.31 \pm 0.08$, the rising and decaying time scales were calculated as 740 ± 50 and 480 ± 30 s in the object frame, respectively.

Cellone, Romero, and Combi (2000) and Cellone et al. (2007b) insisted that violent variations of tens of minutes time scale may have been spurious. We now examine the 15-min variation that we detected in S5 0716+714 along with points proposed by Cellone, Romero, and Combi (2000) and Cellone et al. (2007b). First, the spurious variation in the light curve could have arisen from a variation of the seeing size, because of an effect of the host galaxy (Cellone et al. 2000). However, the host galaxy of S5 0716+714 is so faint that its contribution was negligible to our photometry (Nilsson et al. 2008). Moreover, we confirmed that there is no correlation between the light curve and the temporal variation of the seeing size in our case. Second, if the comparison star was ~ 2 mag brighter than the source, the variation would be severely overestimated (Cellone et al. 2007a). The magnitude of the comparison was 12.48 mag in the V band, as mentioned in section 2, and that of the object was about 12.6 in the same band. The difference of magnitude in the object and the comparison was < 1 mag, and thus we did not overestimate the variation. In order to confirm the significance of the observed bump, we calculated the variability parameter, C (Romero et al. 2002) with the scale factor Γ (Howell et al. 1988 and Cellone et al. 2007b). According to Romero et al. (2002), an object can be considered to be variable (at the 99% confidence level) if their parameters satisfy $C/\Gamma \geq 2.576$. When the magnitudes of the object, comparison and check stars were 12.6, 12.48, and 13.55, Γ was about 0.88, and the scaled variability parameter, C/Γ, around the bump ($t < 17.68$ and $18.27 < t$ in UT) was 5.340. Thus, the bump was not caused by an effect of the magnitudes of the comparison and check stars. Therefore, we conclude that the observed 15-min bump is a real one.

The $V - J$ color became bluer with the overall brightening trend. The color at the end of the observation was 0.025 ± 0.011 mag bluer than that at the start. Also, at the 15-min bump maximum, it became bluer, $\Delta(V - J) = -0.025 \pm 0.011$; this behavior is called "bluer-when-brighter". Such a feature of bluer-when-brighter was also observed in the internight variation of one day time-scale in S5 0716+714. In a long-term trend of tens of days time-scale, however, the feature of bluer-when-brighter was seldom seen (Wagner et al. 1996; Ghisellini et al. 1997). This was the first time that this feature was detected in such a short variability (15-min bump) in optical and NIR bands. Our observation indicates that the microvariability has the same feature as the internight variability. It suggests that the internight variability and the microvariability are caused by the same mechanism, while the long-term variation has a different one.

In our monitoring of S5 0716+714 in 2007, there were the two other days in which we obtained long time-series data, that is, November 3 (3.5 hr) and November 13 (2.5 hr). We investigated whether the frequency of the microvariability was high or low using the scaled variability parameter, C/Γ. For our observations, the scaled the variability parameters, C/Γ, were 1.22 and 1.04 on November 3 and 13, respectively, in the V band. Based on this result, we conclude that the microvariability only appeared on October 20 during our monitoring.

3.2. Polarimetric Observation

The polarization parameters were also variable on October 20. The maximum polarization degree of the object was about 10.5% and the minimum of that was about 7.5%. Figure 2 shows the variation on the Q–U plane. The time-series of the Stokes parameters, Q and U, are depicted in figure 3, along with the V-band light curve for a comparison. The temporal evolution of the Stokes parameters indicates the presence of a variation feature on the Q–U plane associated with the bump. We calculated differential polarization vectors from the overall trend. We assumed that there were two components in the polarization vector: the first component was $\mathbf{P}_{\rm base}(t)$, associated with the overall brightening trend, and the second one was $\mathbf{P}_{\rm diff}(t)$, which was the deviation from $\mathbf{P}_{\rm base}(t)$. They are written as

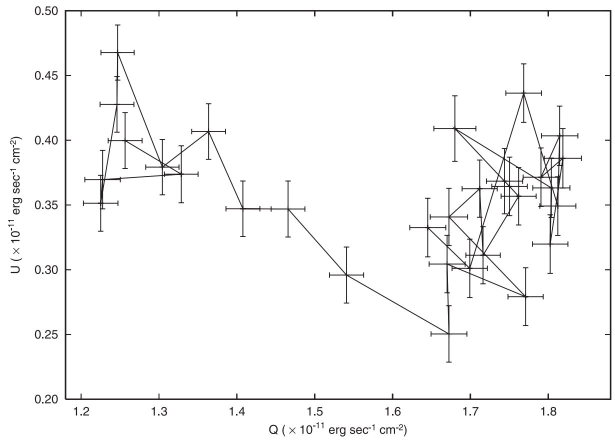

Fig. 2. Stokes Q and U parameters in the V band during observations on 2007 October 20. The Stokes parameters were rebinned to 4 min. The unit of the Q and U is erg s^{-1} cm^{-2}.

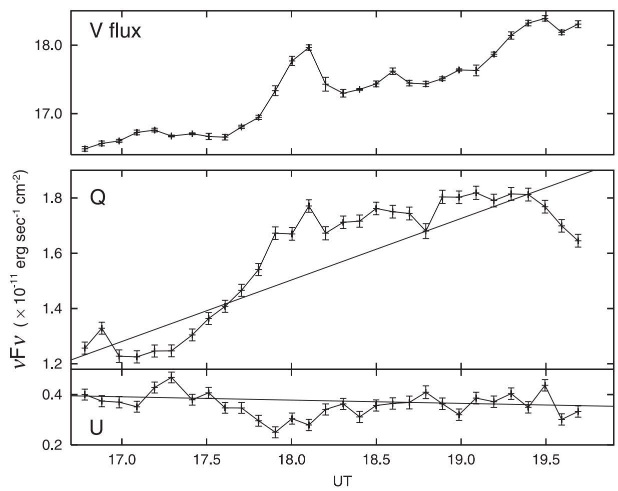

Fig. 3. Top panel: Flux light curve in the V band. Middle and bottom panel: Q and U curves in the same band. The solid lines indicate $\mathbf{P}_{\rm base}(t)$, which is defined in the text. All units of the vertical axis are erg s^{-1} cm^{-2}. The flux was calculated to be 1.98×10^{-5} erg s^{-1} cm^{-2} at 0 mag in the V band (Fukugita et al. 1995).

$$\mathbf{P}_{\rm obs}(t) = \mathbf{P}_{\rm base}(t) + \mathbf{P}_{\rm diff}(t), \quad (2)$$

$$\mathbf{P}_{\rm base}(t) = [Q_{\rm base}(t), U_{\rm base}(t)]. \quad (3)$$

In our analysis, $Q_{\rm base}(t)$ and $U_{\rm base}(t)$ are approximated as linear functions, which were obtained by fitting the data outside of the bump ($t < 17.68$ and $18.27 < t$ in UT), as shown in figure 3. We calculated the differential polarized flux, $PF_{\rm diff}(t) = |\mathbf{P}_{\rm diff}(t)|$, and the angle, $PA_{\rm diff}(t) = 0.5\arctan[U_{\rm diff}(t)/Q_{\rm diff}(t)]$, which are shown in figure 4.

If the bump component has no specific polarization vector, $PF_{\rm diff}(t)$ and $PA_{\rm diff}(t)$ should be mainly constructed by random noise. In figure 4, however, $PF_{\rm diff}(t)$ is correlated with the bump. $PA_{\rm diff}(t)$ dramatically changed just before the bump at 17.5 UT, and then it kept constant during the bump. Thus, the bump had an intrinsic polarization vector, the polarization angle of which was constant. This result is insensitive to the data period used for the definition of the overall trend.

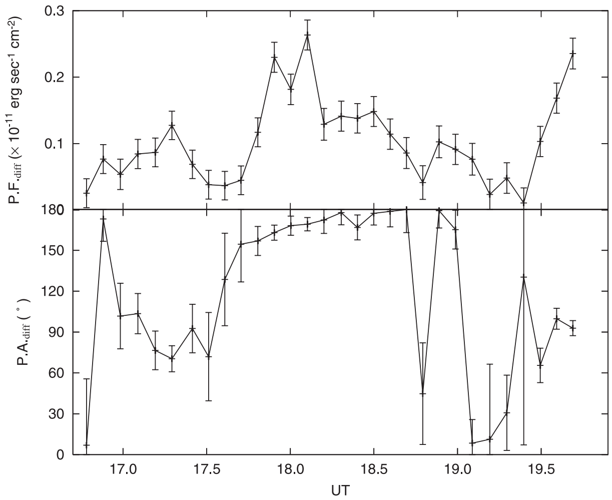

Fig. 4. Time variation of the differential polarization vector from the overall brightening trend. The top figure shows the differential polarized flux, $PF_{\rm diff}(t)$ (erg $\mathrm{s^{-1}\,cm^{-2}}$). At around 18 UT, there is a peak that is associated with the bump. The bottom figure shows the differential polarization angle, $PA_{\rm diff}(t)$ (degree).

Although $PA_{\rm diff}(t)$ apparently continues to be constant even after the bump, it may be an artificial effect, due to the linear fitting to the overall trend.

Figure 4 indicates another bump-like structure in $PF_{\rm diff}(t)$ at 19.5 UT. It can also be associated with a possible bump in the light curve, as can be seen from figures 1 and 3. Thus, such a short bump may frequently appear in the brightest state of S5 0716+714.

4. Discussion

The time-scales in the object frame were 740 ± 50 and 480 ± 30 s in the rising and decaying phases of the bump. The size of the emitting region, R, can be estimated as the light-crossing time, $R < c\Delta\tau$, where c is the speed of light. With a correction of the Doppler boosting, it is now $R < \delta c \Delta\tau$. The Schwarzschild radius for a black-hole mass, M, is defined as $R_{\rm S} = 2GM/c^2$, where G is the gravitational constant. If the object has typical values of the Doppler factor, $\delta \approx 10$, and the black-hole mass $M = 10^9 M_\odot$, the emitting region R is constrained to be $R < (0.49 \pm 0.03)\, R_{\rm S}$. Thus in this case, the variation originated from a quite confined region whose size was smaller than $R_{\rm S}$. We now assume that the bump was caused by variations of the whole area in the jet at a certain distance apart from the black hole. In this situation, we can expect that the emitting region was larger than the Schwarzschild radius, $R > R_{\rm S}$, except for a scenario with an extreme re-confinement of the jet (Sokolov et al. 2004). In this case, however, the emitting region is smaller than $R_{\rm S}$. In order to satisfy $R > R_{\rm S}$, M should be

$$\frac{M}{\delta} < \frac{c^3 \Delta\tau}{2G}. \tag{4}$$

Substituting the decaying time-scale of 480 s into equation (4), we obtain $\delta > (20 \pm 1)\, M/10^9 M_\odot$. The bump could thus originate from the whole area of the jet, if S5 0716+714 has a relatively small black-hole mass or a large Doppler factor.

The whole emitting region in blazars is, however, believed to be not so confined in $1 \cdot R_{\rm S}$. If the emitting region is (5 or 10) $R_{\rm S}$, the relationship with δ and M is about $\delta >$ (100 or 200) $M/10^9 M_\odot$. In general, the optical emitting region is believed to be extended on a sub-pc scale in jets. If the emitting region is located at the sub-pc scale from the black hole, the black-hole mass (or Doppler factor) would be extraordinarily small (or large), in order to explain the bump by a variation of the whole emitting region. Thus, an alternative idea is required. The idea is that the emission region of the microvariability is small, and the local area within the whole area of the jet. This suggestion is consistent with the small amplitude of the magnitude at the bump.

In section 3, we show that the 15-min bump has an intrinsic polarization vector. We estimated the polarization degree of the bump component. The maximum value of the differential polarized flux is $(2.7 \pm 0.5) \times 10^{-12}$ erg $\mathrm{s^{-1}\,cm^{-2}}$. Using the total flux at the bump peak, $(1.02 \pm 0.02) \times 10^{-11}$ erg $\mathrm{s^{-1}\,cm^{-2}}$, the polarization degree of the bump component was calculated to be $27 \pm 5\%$. On the other hand, the observed polarization degree at the bump is $9.8 \pm 0.5\%$. Therefore, the polarization degree of the bump component is much larger than that of the emission component of the overall brightening trend. Hence, the bump presumably originated from the region where the magnetic field is more aligned than that in the emitting region of the overall brightening trend.

On the basis of both the variability time-scale and the polarization behavior, we suggest that the bump originated not from the whole jet, but from the local region where the magnetic field is aligned.

5. Conclusion

We obtained multicolor photometric and polarimetric data of the shortest time-scale variation in S5 0716+714 for the first time. Our findings are summarized as below; first, the object became blue with $\Delta(V\text{–}J) = -0.025$ during the bump. Second, the bump component has a specific polarization vector with a large polarization degree of 27%, which is distinct from the overall brightening trend. It can be suggested that the emitting region of the microvariability in the optical band is a small and local area compared with the whole optical emitting region in the jet.

This work was partly supported by a Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology of Japan (19740104).

References

Aharonian, F., et al. 2007, ApJ, 664, L71
Albert, J., et al. 2007, ApJ, 669, 862
Angel, J. R. P., & Stockman, H. S. 1980, ARA&A, 18, 321
Antonucci, R. 1993, ARA&A, 31, 473
Blandford, R. D., Königl, A. 1979, ApJ, 232, 34
Cellone, S. A., Romero, G. E., & Araudo, A. T. 2007a, MNRAS, 374, 357
Cellone, S. A., Romero G. E., & Combi J. A. 2000, AJ, 119, 1534
Cellone, S. A., Romero G. E., Combi J. A., & Martí, J. 2007b, MNRAS, 381, 60
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Ghisellini, G., et al. 1997, A&A, 327, 61
González-Pérez, J. N., Kidger, M. R., & Martín-Luis, F. 2001, AJ, 122, 2055
Gupta, A. C., Deng, W. G., Joshi, U. C., Bai, J. M., & Lee, M. G. 2008, New Astronomy, 13, 375
Howell, S. B., Warnock, A., III, & Mitchell, K. J. 1988, AJ, 95, 247
Nilsson, K., Pursimo, T., Sillanpää, A., Takalo, L. O., Lindfors, E. 2008, A&A, 487, L29
Raiteri, C. M., et al. 2003, A&A, 402, 151
Romero, G. E., Cellone, S. A., Combi, J. A., & Andruchow, I. 2002, A&A, 390, 431
Skrutskie, M. F., et al. 2006, AJ, 131,1163
Sokolov, A., Marscher, A. P., & McHardy, I. M. 2004, ApJ, 613, 725
Stalin, C. S., Gopal-Krishna, Sagar, R., Wiita, P. J., Mohan, V., & Pandey, A. K. 2006, MNRAS, 366, 1337
Wagner, S. J., et al. 1996, AJ, 111, 2187
Watanabe, M., et al. 2005, PASP, 117, 870
Wu, J., Zhou, X., Ma, J., Wu, Z., Jiang, Z., & Chen, J. 2007, AJ, 133, 1599
Xie, G. Z., Zhou, S. B., Li, K. H., Dai, H., Chen, L. E., & Ma, L. 2004, MNRAS, 348, 831