NEAR-INFRARED POLARIMETRY OF FLARES FROM Sgr A* WITH SUBARU/CIAO

Shogo Nishiyama1,8, Motohide Tamura2, Hirofumi Hatano3, Tetsuya Nagata1, Tomoyuki Kudo2, Miki Ishii4, Rainer Schödel5, and Andreas Eckart6,7
1 Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan; shogo@kusastro.kyoto-u.ac.jp
2 National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
3 Department of Astrophysics, Nagoya University, Nagoya 464-8602, Japan
4 Subaru Telescope, National Astronomical Observatory of Japan, 650 North A’ohoku Place, Hilo, HI 96720, USA
5 Instituto de Astrofísica de Andalucía (IAA)-CSIC, Camino Bajo de Huétor 50, E-18008 Granada, Spain
6 I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany
7 Max Planck Institute für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Received 2009 June 8; accepted 2009 July 30; published 2009 August 13

ABSTRACT

We have performed near-infrared (NIR) monitoring observations of Sgr A*, the Galactic center radio source associated with a supermassive black hole, with the NIR camera CIAO and the 36 element adaptive optics system on the Subaru telescope. We observed three flares in the $K_s$ band (2.15 μm) during 220 minutes monitoring on 2008 May 28, and confirmed the flare emission is highly polarized, supporting the synchrotron radiation nature of the NIR emission. Clear variations in the degree and position angle of polarization were also detected: an increase of the degree of polarization of about 20%, and a swing of the position angle of ~60°–70° in the declining phase of the flares. The correlation between the flux and the degree of polarization can be well explained by the flare emission coming from hotspot(s) orbiting Sgr A*. Comparison with calculations in the literature gives a constraint to the inclination angle $i$ of the orbit of the hotspot around Sgr A*, as 45° ≤ $i$ < 90° (close to edge-on).

Key words: black hole physics – Galaxy: center – polarization – techniques: high angular resolution

1. INTRODUCTION

Sagittarius A* (Sgr A*), the compact source of radio, infrared, and X-ray emission at the center of our Galaxy, is associated with a supermassive black hole (SMBH; Eckart & Genzel 1996; Ghez et al. 2000; Schödel et al. 2002) weighing in at $≈4 \times 10^6 M_\odot$ (Ghez et al. 2008; Gillessen et al. 2009). Since the first identification of Sgr A* in the near-infrared (NIR) wavelengths (Genzel et al. 2003), NIR flares have been studied extensively. Such observations have found that Sgr A* is highly variable, and periodicity of ~20 minutes claimed in some observations (e.g., Genzel et al. 2003; Eckart et al. 2006) would correspond to the black hole mass orbiting around Sgr A*. This is an almost non-stop polarimetric observation of Sgr A* over 220 minutes, and we have detected three main flares and shorter sub-flares superimposed on the underlying main flares. We will show that the profile is fairly well explained in the context of a hotspot orbiting the SMBH.

2. OBSERVATIONS AND DATA ANALYSIS

On 2008 May 28, we conducted $K_s$-band (2.15 μm) polarimetric observations of Sgr A* using CIAO and its polarimeter (Tamura et al. 2003) and AO36 (Takami et al. 2004) on the Subaru telescope (Iye et al. 2004). CIAO provides an image of a 22′′ × 22′′ area of sky with a scale of 21.7 mas pixel$^{-1}$ (Figure 1). With the $R = 13.2$ mag natural guide star USNO 0600–28577051 located about 30′′ from Sgr A*, and stable atmospheric condition during the observations, AO36 provided a stable correction with seeing values between 0′′.17 and 0′′.21 in the $K_s$ band. CIAO employs a rotatable half-wave plate installed in front of the AO and a fixed wire grid polarizer in the cryostat to measure linear polarization. We made 20 s exposures at four wave plate angles in the sequence of 0′′, 45′′, 22′′, and 67.5′′. Including time for readout and rotation of the wave plate, about 200 s is required for one sequence of observation. We observed a dark cloud located at a few arcmin northwest from Sgr A* before and after the observations of Sgr A* to obtain sky measurements. We have performed near-infrared (NIR) monitoring observations of Sgr A*, the Galactic center radio source associated with a supermassive black hole, with the NIR camera CIAO and the 36 element adaptive optics system on the Subaru telescope. We observed three flares in the $K_s$ band (2.15 μm) during 220 minutes monitoring on 2008 May 28, and confirmed the flare emission is highly polarized, supporting the synchrotron radiation nature of the NIR emission. Clear variations in the degree and position angle of polarization were also detected: an increase of the degree of polarization of about 20%, and a swing of the position angle of ~60°–70° in the declining phase of the flares. The correlation between the flux and the degree of polarization can be well explained by the flare emission coming from hotspot(s) orbiting Sgr A*. Comparison with calculations in the literature gives a constraint to the inclination angle $i$ of the orbit of the hotspot around Sgr A*, as 45° ≤ $i$ < 90° (close to edge-on).
The Image Reduction and Analysis Facility (IRAF)\textsuperscript{11} software package was used to perform dark- and flat-field corrections, sky-background estimation, and subtraction followed by bad pixel corrections. A point-spread function was extracted via point-source fitting with the program \textit{StarFinder} (Diolaiti et al. 2000) from each image. Each image was then deconvolved with the Lucy–Richardson algorithm (Lucy 1974; Richardson 1972), and beam restored with a Gaussian beam of FWHM corresponding to the respective wavelengths (66 mas at 2.15 \(\mu\)m). The deconvolved images show clear flares at the position of Sgr A* (Figure 2).

Flux densities of Sgr A* and other point sources were obtained via aperture photometry in Stokes \(I\) images \([I = (I_0 + I_{22:5} + I_{45:} + I_{67:5})/2]\). We used \textit{DAOFIND} and \textit{APPHOT} tasks for point sources identification and photometry. The flux density of each \(I\) image was calibrated with 10 sources in the same field. For extinction correction, we assumed \(A_{K_S} = 2.8\) mag (Eisenhauer et al. 2005). The flux was corrected for a background flux density contribution \(F_{bg}\), which was determined as the mean flux measured in the same aperture size at six different positions, which are free from contributions of individual stars. The photometric error at each flux of Sgr A* was estimated by fitting a power law to the rms uncertainty in the flux for non-variable faint stars of similar flux densities. We found a typical dependence of the photometric error \(\sigma\) on flux \(F\) as \(\sigma = 0.06F^{0.78}\) mJy.

The Stokes parameters \(I, Q,\) and \(U\) for Sgr A* and other point sources were determined by aperture polarimetry as follows. \textit{DAOFIND} and \textit{APPHOT} tasks were used to obtain an intensity for each wave plate angle (\(I_0, I_{22:5}, I_{45:}, I_{67:5}\)) with an aperture radius of 5 pixel (0:11, see a circle in Figure 2). Based on the intensities, we calculated the Stokes parameters as \(I = (I_0 + I_{22:5} + I_{45:} + I_{67:5})/2, Q = I_0 - I_{45:},\) and \(U = I_{22:5} - I_{67:5}\). With these Stokes parameters, the degrees \(P\) and position angles \(\theta\) of polarization for stars in the same field were obtained. We confirmed that \(P = 10.6\%\) and \(\theta = 19:8\) for IRS 21, and 4.8\% and 24\(^\circ\) for mean polarization of field stars; these agree well with the results by Ott et al. (1999). We obtained a small mean rms of the degrees of polarization as 0.9\% for the non-variable faint sources in the same field, suggesting a stable atmospheric condition and a reliable photometry.

To obtain intrinsic degree and position angle of polarization for Sgr A*, contributions of interstellar polarization and a faint nearby star S17 should be taken into account. Here we assume that S17 is an intrinsically unpolarized source. An observed Stokes parameter normalized by intensity, \((Q/I)_{\text{obs}}\), is given by

\[
\left(\frac{Q}{I}\right)_{\text{obs}} \approx \left(\frac{Q_{\text{SgrA*}}}{I_{\text{SgrA*}}} + \frac{Q_{\text{S17}}}{I_{\text{S17}}}\right) + \left(\frac{Q}{I}\right)_{\text{ISM}},
\]

where \(Q_{\text{SgrA*}}\) is a Stokes \(Q\) parameter for Sgr A*, \(I_{\text{SgrA*}}\) and \(I_{\text{S17}}\) are Stokes \(I\) parameters for Sgr A* and S17, respectively, and \((Q/I)_{\text{ISM}}\) is a normalized Stokes \(Q\) parameter for the interstellar polarization. Hence, we can obtain an intrinsic, normalized Stokes \(Q\) parameter for Sgr A* as

\[
\left(\frac{Q_{\text{SgrA*}}}{I_{\text{SgrA*}}}\right) \approx \left(\frac{Q}{I}\right)_{\text{obs}} - \left(\frac{Q}{I}\right)_{\text{ISM}} \times \left(\frac{I_{\text{SgrA*}} + I_{\text{S17}}}{I_{\text{SgrA*}}}\right).
\]

\((Q/I)_{\text{ISM}}\) can be calculated accurately with bright stars in the same fields, as \((Q/I)_{\text{ISM}} = 0.032\) and \((Q/I)_{\text{ISM}} = 0.022\), in the assumption that they are located near the Galactic center and are intrinsically unpolarized. We derived the last term in Equation (2) as \((I_{\text{SgrA*}} + I_{\text{S17}})/(I_{\text{SgrA*}}) = (F_{\text{SgrA*} + \text{S17}} - F_{\text{bg}})/(F_{\text{SgrA*} + \text{S17}} - (F_{\text{S17}} + F_{\text{bg}}))\), where \(F_{\text{SgrA*} + \text{S17}}\) is the total flux density of Sgr A* and S17, \(F_{\text{bg}}\) is a background flux density contribution, and \(F_{\text{S17}} = 6.7\) mJy (dereddened flux; an observed magnitude is 15.3 mag, see Gillessen et al. 2009). With the parameters \((Q_{\text{SgrA*}}/I_{\text{SgrA*}})\) and \((U_{\text{SgrA*}}/I_{\text{SgrA*}})\) and equations

\[
P_{\text{SgrA*}} = \sqrt{\left(\frac{Q_{\text{SgrA*}}}{I_{\text{SgrA*}}}\right)^2 + \left(\frac{U_{\text{SgrA*}}}{I_{\text{SgrA*}}}\right)^2},
\]

\[
\theta_{\text{SgrA*}} = \frac{1}{2} \arctan\left(\frac{U_{\text{SgrA*}}}{I_{\text{SgrA*}}}\right) / \left(\frac{Q_{\text{SgrA*}}}{I_{\text{SgrA*}}}\right),
\]

we can obtain the intrinsic degree \(P_{\text{SgrA*}}\) and the position angle \(\theta_{\text{SgrA*}}\) of polarization for Sgr A*. The position angle \(\theta\) is measured from the north and increasing counterclockwise.

3 RESULTS

The dereddened flux of Sgr A* plus S17 shows a clear variation (Figure 3, top panel, black line). For reference, those for the non-variable faint sources in the same field are also shown in the same panel (colored lines). There are three major peaks: the broadest, and the weakest flare from \(t = 0\) to 90 minutes, the strongest flare from 145 to 190 minutes, in which a peak is followed by a bump, and the narrowest peak with the shortest rise/decay time from 195 to 210 minutes. The AO system did not work at \(t = 131–145\) minutes; therefore, if there was a flare around 130 minutes, we missed that. In the first flare, sub-structures might exist around 60 minutes. The rise/decay timescale of \(\sim 6.5\) minutes in the third flare is consistent with the light crossing timescales for the inner part of the accretion disk, less than 10 Schwarzschild radii, around a \(4 \times 10^6\) \(M_\odot\) black hole.

\textsuperscript{11} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 2. Ks-band images of the central 1′′ × 1′′ region. The time from the beginning of the observation is 145.1 (left) and 158.4 minutes (right). In each image, the location of Sgr A* is marked by a circle, and a faint star (S17) is also located in the circle. The image scale is logarithmic, and the integration time is 20 × 4 s. The images were sky-subtracted, flat-fielded, corrected for bad pixels and cosmic rays, and deconvolved with the Lucy–Richardson algorithm.

The middle and bottom panels in Figure 3 represent time evolutions of Q/I and U/I, respectively, for Sgr A* plus S17 flux (black line), and other faint sources in the same field (colored lines). The colored lines show nearly constant values. The variation of Q/I for Sgr A* is much larger than those of the other sources. In the equatorial coordinates, the variation in U/I of Sgr A* is smaller than Q/I. The error bars of Q/I and U/I for Sgr A* were determined from the mean rms of Q/I and U/I for the non-variable faint sources of similar flux densities.

We find clear variations in the intrinsic degree of polarization $P_{\text{SgrA}^*}$ and the position angle $\theta_{\text{SgrA}^*}$ of Sgr A* (Figure 4). The polarization was often detected with not more than 2σ, and thus we will focus our discussion on the observations where $P_{\text{SgrA}^*}$ was detected with more than 2σ (thin red lines in Figure 4) and more than 4σ (thick red lines) levels. The first and second flares consist of a weakly or non-polarized main flare and a highly polarized sub-flare. The $P_{\text{SgrA}^*}$ rises slowly up to ∼22% and probably decays sharply in the first flare. In the second flare, $P_{\text{SgrA}^*}$ rises again up to ∼19%. Both rises occur after the bright flare phase, when the flux of Sgr A* is decaying. These profiles are consistent with the previous observations (Meyer et al. 2006b; Trippe et al. 2007; Eckart et al. 2008). The variation in $\theta_{\text{SgrA}^*}$ is complex: $\theta_{\text{SgrA}^*}$ swings from ∼70° to ∼10° in the first flare. The behavior of $\theta_{\text{SgrA}^*}$ between the first and second flares is not clear due to large uncertainties, but $\theta_{\text{SgrA}^*}$ swings from ∼70° to ∼−10° in the second flare. Due to the short duration of only ∼13 minutes, binning of the data points makes it impossible to trace the variation of $P_{\text{SgrA}^*}$ and $\theta_{\text{SgrA}^*}$ in the third flare.

4. DISCUSSION

So far, the time evolutions of polarization of Sgr A* in the NIR bands have been obtained just for the four flares on 2004 June 12, 2005 July 29, 2006 May 31, and 2007 May 15 (Eckart et al. 2006, 2008; Meyer et al. 2006a, 2006b; Trippe et al. 2007; Zamaninasab 2008). As pointed out by Trippe et al. (2007), the observed polarization parameters, in particular the position angle, in the first three flares show “remarkable permanence,” and the last 2007 flare has also similar parameters in spite of some differences (Eckart et al. 2008). In the typical flare in 2006, the degree of polarization rises up to 30%−40%, and simultaneously, the position angle swings about 70° in the decay phase of the broad underlying flare (Meyer et al. 2006b; Trippe et al. 2007).

The first flare we observed shows similar properties to those detected in the previous observations. It shows a rise in $P_{\text{SgrA}^*}$ and a swing in $\theta_{\text{SgrA}^*}$ at $t \gtrsim 50$ minutes, where the long flare (duration of more than 90 minutes) is slowly fading away. The observed $\theta_{\text{SgrA}^*}$ during the flare peak is ∼60°, which agrees well
with $60\pm20^\circ$ of the flare measured by Eckart et al. (2006), and $80\pm10^\circ$ by Meyer et al. (2006b).

Such flares can be explained with a hotspot model. Eckart et al. (2006) made fitting for the flares in 2004 and 2005 with a two-component (hotspot plus disk) model. For the flares in 2005 and 2006, Meyer et al. (2006a, 2006b) adopted a hotspot plus ring model, which leads to reasonable fits of polarimetric light curves. In their models, the broad overall flare is caused by a time-varying underlying disk or ring, and the shorter sub-flares are due to a hotspot on a relativistic orbit around the SMBH. Eckart et al. (2008) proposed a temporary disk with a short jet model, in which quasi-periodic variation is due to hotspots on the disk.

The second flare from 145 to 190 minutes seems to be different from other polarized flares. The flare survives only for $\sim30$ minutes, and is not superimposed on a broader underlying flare. However, similarly to the previous flares, the second flare shows sub-structures; the highest peak is followed by a lower peak or a bump structure. The two peaks are separate in time by about 15 minutes, which is very similar to a quasi-periodicity of $15.5\pm2$ minutes obtained by Meyer et al. (2006a), so these sub-structures can be explained by periodic orbital motions of a single hotspot. If we consider the time evolution of degree of polarization, however, we can find similarities between our results and the expected light curves for a single orbital motion of a hotspot (Broderick & Loeb 2006).

Many authors calculated light curves from an emitting bright spot on the surface of an accretion disk and comoving with the disk (e.g., Pineault 1981; Asaoka 1989; Bao 1992; Fukue 2003). Recently, Broderick & Loeb (2006) calculated light curves in infrared wavelengths, including polarization, associated with a hotspot orbiting the SMBH in the Galactic center. The primary feature of the light curves with a large orbital inclination angle $i$ (close to the edge-on view) is a narrow and higher peak followed by a broad lower peak/bump. The first peak is formed by a gravitational lensing effect which is strongest when the hotspot is right behind the black hole. Doppler effect and beaming due to the relativistic motion of the hotspot in the approaching regime make the second peak/bump. The time evolutions of polarized flux show a double-peak profile with a higher second peak than the first one, or a slow-rise and sharp-decay profile (with a lower time resolution). The variation of the position angle is mainly influenced by the inclination angle $i$.

The similarities between the second flare and the calculations by Broderick & Loeb (2006) suggest that the second flare could be explained with a single orbital motion of a hotspot. In the light curve of the second flare from 145 to 190 minutes, we can see the “first peak and second peak/bump” profile. In the time evolution of degree of polarization, it is clearly seen that $P_{\text{SgrA}^*}$ increases in the decay phase of the flare. The profiles of $P_{\text{SgrA}^*}$ are asymmetric, showing slow rise and sharp decay. If the observed time evolution of polarization comes from such a hotspot, comparison with calculations allows us to investigate the inclination angle $i$ of the hotspot orbits around Sgr A*, because the time evolution profile of the flux and the degree of polarization strongly depend on the inclination angle. Broderick & Loeb (2006) showed that when $i \geq 67.5^\circ$, light curves show a bump after the first peak. In addition, the time evolution of polarization has a double-peak or slow-rise and sharp-decay profile. These are very similar to the second flare in our observations. When $i \leq 45^\circ$, by contrast, the light curve has a smooth decay phase and the polarization shows a symmetric or slow-decay profile. These comparisons could exclude a small inclination angle (near face-on) of $i \leq 45^\circ$. This is consistent with recent results, $i \gtrsim 20^\circ$ by Meyer et al. (2006b), $i \gtrsim 35^\circ$ by Meyer et al. (2006a), $i \gtrsim 50^\circ$ by Meyer et al. (2007), and $i \approx 70^\circ$ with which Eckart et al. (2008) found a minimum reduced-$\chi^2$ value in the modeling of the observed time evolution of flux and polarization.

Although the hotspot model is a favorite model with our results, it is premature to use such a simple model to draw strong conclusions. For example, Trippe et al. (2007) proposed that the swing of the position angle in NIR polarization is caused by either a magnetic field geometry changes due to a vanishing of the accretion disk, or materials move out of the accretion disk, perhaps into a jet. A model of the expansion of hot self-absorbed synchrotron plasma blob was also proposed from multi-wavelength observations (e.g., Yusef-Zadeh et al. 2006, 2008; Marrone et al. 2008). This model explains the time delay between different wavelengths in flare emissions, while the hotspot model does not. Meyer et al. (2008) and Do et al. (2009) reported non-detection of a statistically significant periodicity in NIR light curves. Based on the model to a two-temperature magnetorotational instability driven accretion flow by Liu et al. (2007), Huang et al. (2008) showed the spectrum and frequency-dependent polarization for Sgr A* with general relativistic effects, and explain the 90° flip of the position angle between submillimeter and NIR observations.

Although time-resolved light curves have been presented by many authors (e.g., Goldston et al. 2005; Falanga et al. 2007), no “time-resolved, polarized” light curves have been available for the models other than those by Broderick & Loeb (2006). Polarization provides new information which is extremely useful to break degeneracy of various model parameters. Our observations demonstrated that it is now possible to monitor the polarimetric variation of Sgr A* continuously up to $\sim10$ hr by combining contiguous Subaru and VLT observations, as done.
for the NIR flux density using VLT and Keck observations (Meyer et al. 2008). Simulations including polarization evolution to test the various models for Sgr A* are now strongly encouraged.

This work was supported by a Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

REFERENCES

Asaoka, I. 1989, PASJ, 41, 763
Bao, G. 1992, A&A, 257, 594
Broderick, A. E., & Loeb, A. 2006, MNRAS, 367, 905
Diolaiti, E., et al. 2000, A&A, 147, 335
Do, T., Ghez, A. M., Morris, M. R., Yelda, S., Meyer, L., Lu, J. R., Hornstein, S. D., & Matthews, K. 2009, ApJ, 691, 1021
Eckart, A., & Genzel, R. 1996, Nature, 383, 415
Eckart, A., Schödel, R., Meyer, L., Trippe, S., Ott, T., & Genzel, R. 2006, A&A, 455, 1
Eckart, A., et al. 2008, A&A, 479, 625
Eisenhauer, F., et al. 2005, ApJ, 628, 246
Falanga, M., Melia, F., Tagger, M., Goldwurm, A., & Bélanger, G. 2007, ApJ, 662, L15
Fukue, J. 2003, PASJ, 55, 1121
Genzel, R., & Karas, V. 2007, in IAU Symp. 238, Black Holes from Stars to Galaxies—Across the Range of Masses, ed. V. Karas & G. Matt (Cambridge: Cambridge Univ. Press), 173
Genzel, R., Schödel, R., Ott, T., Eckart, A., Alexander, T., Lacombe, F., Rouan, D., & Aschenbach, B. 2003, Nature, 425, 934
Ghez, A. M., Morris, M., Becklin, E. E., Tanner, A., & Kremenek, T. 2000, Nature, 407, 349
Ghez, A. M., et al. 2008, ApJ, 689, 1044
Gillessen, S., Eisenhauer, F., Trippe, S., Alexander, T., Genzel, R., Martins, F., & Ott, T. 2009, ApJ, 692, 1075
Goldston, J. E., Quataert, E., & Igumenshchev, I. V. 2005, ApJ, 621, 785
Huang, L., Liu, S., Shen, Z.-Q., Cai, M. J., Li, H., & Fryer, C. L. 2008, ApJ, 676, L119
Iye, M., et al. 2004, PASJ, 56, 381
Liu, S., Qian, L., Wu, X.-B., Fryer, C. L., & Li, H. 2007, ApJ, 668, L127
Lucy, L. B. 1974, AJ, 79, 745
Marrone, D. P., et al. 2008, ApJ, 682, 373
Meyer, L., Do, T., Ghez, A., Morris, M. R., Witzel, G., Eckart, A., Belanger, G., & Schödel, R. 2008, ApJ, 688, L17
Meyer, L., Eckart, A., Schödel, R., Duschl, W. J., Mužić, K., Dovčiak, M., & Karas, V. 2006a, A&A, 460, 15
Meyer, L., Schödel, R., Eckart, A., Duschl, W. J., Karas, V., & Dovčiak, M. 2007, A&A, 473, 707
Meyer, L., Schödel, R., Eckart, A., Karas, V., Dovčiak, M., & Duschl, W. J. 2006b, A&A, 458, L25
Ott, T., Eckart, A., & Genzel, R. 1999, ApJ, 523, 248
Pineault, S. 1981, ApJ, 246, 612
Richardson, W. H. 1972, J. Opt. Soc. Am., 62, 55
Schödel, R., et al. 2002, Nature, 419, 694
Takami, H., et al. 2004, PASJ, 56, 225
Tamura, M., Fukagawa, M., Murakawa, K., Suto, H., Itoh, Y., & Doi, Y. 2003, Proc. SPIE, 4843, 190
Trippe, S., Paumard, T., Ott, T., Gillessen, S., Eisenhauer, F., Martins, F., & Genzel, R. 2007, MNRAS, 375, 764
Yusef-Zadeh, F., Wardle, M., Heinke, C., Dowell, C. D., Roberts, D., Baganoff, F. K., & Cotton, W. 2008, ApJ, 682, 361
Yusef-Zadeh, F., et al. 2006, ApJ, 644, 198
Zamaninasab, M., et al. 2008, J. Phys. Conf. Ser., 131, 012008