Suzaku Observations of the Supernova Remnant N23 in the Large Magellanic Cloud

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(Received 2010 May 8; accepted 2010 July 23)

Abstract

X-ray emission from the supernova remnant N23 in the Large Magellanic Cloud (LMC) has been studied using the X-ray Imaging Spectrometer (XIS) onboard Suzaku. Thanks to a superior energy resolution of the XIS in the soft X-ray band, we resolved H-like and He-like Oxygen Kα emission lines from N23 with unprecedentedly high quality, and as a result, identified a new optically thin thermal emission component with a temperature of ~0.2 keV, as well as that with a temperature of ~0.5–0.7 keV, previously known. This alters the estimate of the ionization timescale, $n_{e,f}$, from $\sim 10^{10–11}$ cm$^{-3}$ s to $\gtrsim 10^{12}$ cm$^{-3}$ s. Under the assumption that N23 is still in the Sedov phase, its age, evaluated from the newly discovered low-temperature component, is ~8000 yr, although it is possible that N23 has already moved into the radiative phase. The abundances of the heavy elements are found to be roughly consistent with those of the LMC average, which indicates that the origin of the X-ray emission of N23 is swept-up ambient material, as expected from its ionization timescale.

Key words: ISM: individual (N23) — ISM: supernova remnants — shock waves — X-rays: ISM

1. Introduction

The chemical evolution of the universe has been one of the major issues in modern astronomy. Heavy elements, or metals, have been generated and accumulated in the universe since its birth, mainly through supernovae. An important clue to understand the chemical evolution of the universe will no doubt be brought about by a systematic study of a well-defined sample of supernova remnants. In X-ray observations, we are able to extract information about the plasma temperature, metal abundance, explosion energy, ionization age, and so on from optically thin thermal plasma emission from supernova remnants (SNRs). These pieces of information will lead to our understanding the galactic chemical evolution and star-formation history. A systematic study of SNRs in the Large Magellanic Cloud (LMC) is well-suited for this purpose, because of its well-known distance (50 kpc: Feast 1999) and small interstellar absorption to LMC. The fact that LMC is face-on to us is another advantage. Because of these characteristics, systematic X-ray studies of thermal SNRs in LMC have been carried out with some major X-ray observatories (e.g., Hughes et al. 1998). These observations are, however, limited in terms of energy resolution in the low-energy band below ~1 keV, which is important to study the nature of the SNR plasma in detail, because the temperature of the plasma in most SNRs is less than ~2 keV. In particular, H-like and He-like Oxygen Kα lines that appear in 0.5–0.7 keV dominate a spectrum of the plasma with a temperature of ~1 keV, and hence high-resolution spectroscopy in this energy band is of great importance for evaluating the parameters of the low-temperature plasma, such as the temperature, the density, the ionization parameter and the abundances of the metal. We have therefore decided to perform a systematic study of the SNRs in LMC with the Suzaku XIS (Mitsuda et al. 2007; Koyama et al. 2007), which has the best energy resolution in the Oxygen 0.5–0.7 keV energy band among the CCDs currently in orbit. In this paper, we consider the SNR N23, as a beginning of our systematic study project.

N23 is identified as a SNR by radio observations at 5 and 14.7 GHz for the first time (Milne et al. 1980). Its X-ray emission extends $100' \times 120'$ in the sky ($24 \text{ pc} \times 29 \text{ pc}$ at a distance of 50 kpc), showing a semi-circular morphology with only the south-eastern hemisphere being bright (Hughes et al. 2006). Based on the ASCA observation, Hughes et al. (1998) classified N23 as a young SNR with an age of ~3800 yr from the spectrum of the entire remnant. Hughes et al. (2006) carried out spatially resolved spectroscopy of N23 with Chandra, and estimated the age of the north-western rim to be ~4600 yr. These observations result in a consistent estimation of the temperature and the ionization parameter ($n_e, t$) in the bright south-eastern shell, which is ~0.5–0.7 keV and ~$10^{10–11}$ cm$^{-3}$ s, respectively. They are, however, not be able to resolve H-like and He-like Kα lines from Oxygen clearly because of a limited energy resolution below ~1 keV. In addition, Hughes et al. (2006) have revealed that there is a point source around the center of N23. From its 0.5–10 keV flux ($\sim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) and power-law spectrum with a photon index of 2.2, the source is probably a rotation-powered pulsar and/or a pulsar wind nebula. If so, the progenitor of N23 is a core-collapsed massive star (Hayato et al. 2006).

This paper is organized as follows. After describing how the observation and data reduction are carried out in section 2, we report on the results of a spectral analysis of N23 in section 3. Owing to the high spectral resolution of the XIS in the Oxygen...
Kα band, we have clearly resolved the H-like and He-like Kα emission lines from Oxygen for the first time, which leads to the identification of a new low-temperature component. Based on these results, we discuss the plasma parameters and evolutionary phase of N23 in section 4. Finally, a summary is given in section 5.

2. Observation and Data Reduction

N23 was observed with Suzaku (Mitsuda et al. 2007) on 2005 August 16–17. The observation log is summarized in table 1. Suzaku is equipped with four modules of the XIS (Koyama et al. 2007). One of them adopts a back-illuminated CCD (BI-CCD), which is referred to as XIS 1, having a superior quantum efficiency, especially in a low-energy band, whilst the other three modules (XIS 0, XIS 2, and XIS 3) utilize front-illuminated (FI) CCDs that have high sensitivity in a high-energy band, and better energy resolution than the BI-CCD. They are adapted at the focal plane of the X-Ray Telescopes (XRT: Serlemitsos et al. 2007). They are thin-foil-nested X-ray mirrors realizing a high throughput in 0.2–12 keV with a moderate imaging capability (1.8–2.3 in half-power diameter). A Suzaku XIS image of N23 below 2 keV is shown in figure 1.

Data reduction and analysis of the present data were carried out using the HEADAS software package version 6.5.1. The data processed by Suzaku pipeline processing software (ver. 2.0) were analyzed. We only used the data taken with the 5 × 5 editing mode in the high and super-high data rates, because of the editing mode of 2 × 2 has uncertainty in the response matrices of the XIS. In screening the data, we removed time intervals while the elevation angle from the night Earth was less than 5°. In the standard data-screening procedure, the time interval during which the elevation angle from the day Earth is less than 20°. This results in, however, only 5.6 ks data being available. We thus reduced the day-Earth elevation angle by degrees by closely comparing the resulting spectra, and have finally found that the solar X-ray contamination does not raise any spectral modification even if we reduce the threshold of the day Earth elevation down to 5° (DYELVIN > 5°) for the XIS data. Owing to this study, the total exposure time has increased to 7.1 ks.

3. Spectral Models

3.1. Extraction of Source and Background Photons

In extracting source photons, we adopted a circular aperture with a radius of 3.3 centered on N23 (the green circle centered on N23 in figure 1). For the background, we have collected photons from the entire CCD area out of the source extraction region, except for the outer edge regions illuminated by 55Mn isotopes adapted in the camera bodies of all the XIS modules, the central circular region with a radius of ~1.5, and the 3.3 circular region centered on the other SNR DEM L71. We combined the spectra from the XIS by adopting the FI-CCDs (XIS 0, XIS 2, and XIS 3) into a single spectrum, and refer to it as the FI spectrum hereafter. The BI spectrum is the same as that solely from the XIS 1 data.

In the spectral analysis, we used XSPEC version 11.3.2aj. The XIS response matrix (RMF) and auxiliary response file (ARF) were calculated using XISRMFGEN (version 2007-05-14) and XISSIMARFGEN (version 2008-04-05), respectively (Ishisaki et al. 2007). The RMFs and ARFs from the FI-CCDs were combined with the ftools ADDRMF and MARFRMF.

3.2. Spectral Models

From the ASCA observations of LMC SNRs, it has been found that the spectra of N23 is well represented by an optically thin thermal-emission model in ionization non-equilibrium (Hughes et al. 1998). In characterizing the spectra of SNR, we thus adopt the non-equilibrium ionization model, or VNEI model in the XSPEC model library. The VNEI model provides the plasma temperature $kT_e$, the ionization timescale $n_e t$, where $t$ is the elapsed time since the shock occurs, the metal abundances, and the normalization parameter $10^{-18}/(4\pi D^2) \int n_e n_H dV$, where $D$ is the distance to the source; $n_e$ and $n_H$ are the electron and hydrogen density, respectively, and $dV$ is the volume element of the SNR.
The emission spectra are attenuated by photoelectric absorption due to metals contained in the interstellar matter within our galaxy and LMC. Since the metal abundances of these two absorption components are significantly different, we consider them separately in the spectral evaluation as follows. We assume solar composition (Anders & Grevesse 1989) for the absorbing matter in the Galaxy, and denote its hydrogen column density as $N_H$. The value of $N_H^G$ toward N23 was obtained by the Galactic H I survey, which is $5.8 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). We utilized the PHABS model in XSPEC to represent the galactic absorption, and freeze $N_H^G$ at these values in the spectral fitting described below. The average metal abundances of LMC, on the other hand, were measured by Russell and Dopita (1992), which is $\sim 0.3$ solar on average over the major metals. We reflected these abundances on the PHABS model, and set the column density associated with LMC $N_H^L$ free to vary in the following spectral fit process.

In evaluating the spectrum of N23 through spectral fitting, we began with a single component VNEI model attenuated by photoelectric absorption. Since the carbon abundances cannot be constrained because of the large interstellar absorption at the carbon Kα line energies, we fixed it to the LMC value (Russell & Dopita 1992). In the early phase of the Suzaku mission, the energy gain had a large uncertainty (Koyama et al. 2007). The gain uncertainty was $\sim \pm 10$ eV, according to previous studies on SNRs (Bamba et al. 2008; Yamaguchi et al. 2008). We therefore have allowed the energy offset to be floated. As a result, the energy offset was converged to $\sim -8$ eV and $\sim -1$ eV, for the FI and BI spectra, respectively. These gain offset values are within the gain uncertainty. The results are summarized in the second column of table 2, labelled ‘1 kT 1 nt’. The best-fit results in $kT_e \simeq 0.548$ keV and log$(n_{e, t} \text{ [cm}^{-3} \text{s}]) \simeq 10.51$ with a $\chi^2$ (d.o.f.) of 144 (99). These parameters are roughly consistent with those from the Chandra observation. Note that, if we do not float the energy gain, the best-fit parameters are $kT_e \simeq 0.552$ keV and log$(n_{e, t} \text{ [cm}^{-3} \text{s}]) \simeq 10.54$ with a $\chi^2$ (d.o.f.) of 219 (101). Hence, the energy offset adjustment significantly improves the fit, while the differences in the temperature and the ionization timescale (in logarithm) are within $\sim 1\%$.

As can be noticed from this table, however, the single-component VNEI model no longer provides an acceptable fit ($\chi^2$ $\simeq 1.5$). We thus appended another VNEI model. To reduce the number of model parameters as much as possible, we constrained either $kT_e$ or $n_{e, t}$ common between the two VNEI components, and fit them to the data separately. The resultant best-fit parameters are also listed in table 2, labelled ‘1 kT 2 nt’ and ‘2 kT 1 nt’, respectively. Although the 1 kT 2 nt model improves the fit significantly, the reduced $\chi^2$ value indicates that it is still not acceptable. The improvement of the 2 kT 1 nt model, on the other hand, is more remarkable, and it provides an acceptable fit at the 90% confidence level. The best-fit model is shown in figure 2. This result indicates that there exists another optically thin thermal plasma component with a temperature of $\sim 0.2$ keV, in addition to the $0.5$–$0.6$ keV component so far known. The discovery of the new low-temperature component is brought about by the clear resolution of the Oxygen Kα lines by the Suzaku XIS. Consequently, the best-fit value of the ionization timescale now becomes log$(n_{e, t} \text{ [cm}^{-3} \text{s}]) \gtrsim 12$. This is significantly larger than that from the ASCA and Chandra observations ($10^{10}$–$10^{11}$ cm$^{-3}$ s$^{-1}$).

In the Chandra observation, more than $\sim 30\%$ of the total emission comes from the eastern rim (Hughes et al. 2006). Since our Suzaku observation covers the remnant entirely, the best-fit parameters that we have obtained are a kind of mean weighted values mainly on this extended bright rim region (see figure 3).

| Parameters | 1 kT 1 nt | 1 kT 2 nt | 2 kT 1 nt | 2 kT 2 nt |
|------------|-----------|-----------|-----------|-----------|
| $N_H^G$ ($\times 10^{20}$ cm$^{-2}$) | 5.8 (fix) | 5.8 (fix) | 5.8 (fix) | 5.8 (fix) |
| $N_H^L$ ($\times 10^{21}$ cm$^{-2}$) | 1.6 (1.3–1.9) | $<$ 0.16 | 1.5 (0.6–1.9) | 0.9 (0.6–1.9) |
| $kT_{e, 1}$ (keV) | 0.548 (0.544–0.567) | 0.572 (0.557–0.580) | 0.569 (0.556–0.593) | 0.581 (0.551–0.597) |
| $kT_{e, 2}$ (keV) | — | — | 0.218 (0.214–0.230) | 0.225 (0.214–0.230) |
| log$(n_{e, t})_1$ (cm$^{-3}$s) | 10.51 (10.48–10.55) | 10.50 (10.45–10.52) | 13.68 (11.92–13.70) | 12.04 (11.87–13.70) |
| log$(n_{e, t})_2$ (cm$^{-3}$s) | — | 13.18 (12.77–13.70) | — | 13.63 (13.27–13.70) |
| Normalization$_1$ ($\times 10^{-2}$) | 1.87 (1.74–1.90) | 0.34 (0.31–0.68) | 0.83 (0.64–1.00) | 0.78 (0.66–0.98) |
| Normalization$_2$ ($\times 10^{-2}$) | — | 0.73 (0.67–0.81) | 2.54 (1.93–2.96) | 1.93 (1.47–3.51) |
| C | 0.30 (fix) | 0.30 (fix) | 0.30 (fix) | 0.30 (fix) |
| N | $<$ 0.02 | 0.09 (0.04–0.25) | 0.54 (0.12–1.05) | 0.37 (0.23–0.94) |
| O | 0.093 (0.089–0.098) | 0.27 (0.26–0.28) | 0.33 (0.25–0.50) | 0.34 (0.28–0.49) |
| Ne | 0.15 (0.14–0.16) | 0.43 (0.39–0.46) | 0.49 (0.35–0.70) | 0.49 (0.40–0.66) |
| Mg | 0.14 (0.12–0.17) | 0.31 (0.27–0.35) | 0.39 (0.33–0.60) | 0.39 (0.32–0.47) |
| Si | 0.28 (0.19–0.36) | 0.34 (0.24–0.43) | 0.41 (0.30–0.52) | 0.42 (0.32–0.55) |
| Fe | 0.111 (0.105–0.117) | 0.18 (0.17–0.22) | 0.24 (0.19–0.33) | 0.24 (0.19–0.33) |
| $\chi^2$ (d.o.f.) | 1.45 (99) | 1.11 (97) | 1.00 (97) | 1.00 (96) |
| Offset FI (eV) | $-8.7 \sim -11.0$ | $-8.1 \sim -9.1$ | $-8.1 \sim -9.0$ | $-8.0 \sim -9.0$ |
| Offset BI (eV) | $-1.0 \sim -1.6$ | $-1.0 \sim -2.1$ | $-1.0 \sim -2.8$ | $-0.3 \sim -1.3$ |

* The errors in the parentheses represent the 90% confidence intervals.
† In units of $10^{-14}$/(4$\pi$D$^2$)$ \int n_e n_H dV$ cm$^{-3}$, where V and D are the volume and distance to the plasma, respectively.

The Chandra observation. Note that, if we do not float the energy gain, the best-fit parameters are $kT_e \simeq 0.552$ keV and log$(n_{e, t} \text{ [cm}^{-3} \text{s}]) \simeq 10.54$ with a $\chi^2$ (d.o.f.) of 219 (101). Hence, the energy offset adjustment significantly improves the fit, while the differences in the temperature and the ionization timescale (in logarithm) are within $\sim 1\%$.
Fig. 3. Smoothed Chandra image of N23 (a) in the 0.2–0.8 keV band and (b) in the 1.5–2.0 keV band. The contours are overlaid with labels of 1.0, 5.0, 15.0 (left) and 0.1, 0.5, 1.0 counts pixel$^{-1}$.
1997), however, no CO emission was discovered from a region including N23. We thus consider that N23 explodes into a relatively dense part of the ISM (~10 cm⁻³). It is suggested this high density is related geometrically with the open cluster HS 114 (Hodge & Sexton 1966) near the remnant (Hughes et al. 2006). Finally, the total ejecta mass is given by \( M_{\text{low}} + M_{\text{high}} \), where \( M_{\text{low}} \) and \( M_{\text{high}} \) are the mass of the low and high-temperature components, respectively. The total ejecta mass is therefore calculated to be \( \approx 30 M_{\odot} \). Hence, the plasma chiefly comprises of the swept-up ISM.

### 4.2. SNR Phase

In this section, we consider the evolutionary phase of N23 by comparing various timescales evaluated from the observed parameters. We compared the Sedov time scale \( t_{\text{Sedov}} \), the plasma age \( t_{\text{ion}} \), estimated from the ionization parameter, and the cooling time scale \( t_{\text{cool}} \) of N23. \( t_{\text{Sedov}} \) is based on the concept of the Sedov simple blast wave model (Sedov 1959), in which a supernova with explosion energy \( E_0 \) expands into the homogeneous ISM, which is given by

\[
t_{\text{Sedov}} = 4.3 \times 10^2 \left( \frac{R}{1 \text{ pc}} \right) \left( \frac{k T_c}{1 \text{ keV}} \right)^{-0.5} \text{yr}, \tag{1}
\]

where \( R \) is the blast wave shock radius and \( T_c \) is the shock temperature; \( t_{\text{cool}} \) is defined as the time scale of the temperature distribution having started to deviate from that of the Sedov model, which is written as

\[
t_{\text{cool}} = 2.7 \times 10^4 \left( \frac{E_0}{10^{51} \text{erg}} \right)^{0.24} \left( \frac{n_0}{1 \text{cm}^{-3}} \right)^{-0.52} \text{yr} \tag{2}
\]

(Falle 1981). If \( t_{\text{cool}} \approx t_{\text{Sedov}} \) holds, the SNR is considered to locate at a late stage of the Sedov phase, or at an initial radiative phase. If, on the other hand, \( t_{\text{Sedov}} < t_{\text{cool}} \) holds, the SNR is regarded as being still in the Sedov phase. We assume that the explosion energy is \( 10^{51} \text{erg} \) in equation (2).

We discovered the new soft emission component with a temperature of \( \approx 0.22 \text{keV} \), in addition to the 0.5–0.7 keV component so far known. Accordingly, we need to update the remnant age estimation. The Sedov time scale and the cooling time scale calculated with equations (1) and (2) are summarized in table 4, together with the ionization age, \( t_{\text{ion}} \), obtained based on the spectral fit. Since the spectral fit with the ‘2kT 1nt’ model provides only the lower limit for the ionization timescale, \( n_{\text{f}}t_{\text{ion}} \), we only have a lower limit for \( t_{\text{ion}} \). We have thus decided to estimate the remnant age with equations (1) and (2).

Using equation (1) with \( R = 8.5 \text{pc} \), \( t_{\text{Sedov}} \) estimated from the low and high-temperature components becomes \( \approx 8000 \text{ and } \approx 5000 \text{yr} \), respectively, which are consistent with the lower limit of \( t_{\text{ion}} \). This is a direct consequence of equation (1), implying \( t_{\text{Sedov}} \) being proportional to \( T_{\text{cool}}^{-1/2} \). The high-temperature component is younger than the low-temperature component. In the Sedov scheme, this can be interpreted as the high-temperature component being heated recently. On the other hand, \( t_{\text{cool}} \) of the low and high-temperature components are \( 9300 f_{0.1}^{0.26} \text{yr} \) and \( 12000 f_{0.1}^{0.26} \text{yr} \), respectively, using equation (2) with \( n_0 \) given in table 3 (subsection 4.1). Since \( t_{\text{Sedov}} \sim t_{\text{cool}} \) for both components, N23 is likely to be at a late stage of the Sedov phase, and if so, its age is \( \approx 8000 \text{yr} \) from the newly discovered low-temperature component.

Note, however, that this discussion depends on the estimation of the volume filling factor, \( f \). Accounting for the highly anisotropic image (figure 3), we normalized \( f \) by 0.1. However, if the shock wave of N23 propagates in a higher density ISM, like the edge of the open cluster HS 114 (Hodge & Sexton 1966), the total volume should be smaller for the given emission measure, resulting in a smaller \( f \). If, for instance, \( f = 0.01 \), \( t_{\text{cool}} \) of the low and high-temperature components are \( \sim 5000 \text{ and } \sim 7000 \text{yr} \), respectively. Since \( t_{\text{cool}} \lesssim t_{\text{Sedov}} \), the low-temperature component should be regarded as being in the radiative phase. In addition, we would also like to remark that, in subsection 4.1, we calculated the plasma volume, while assuming that the shell thickness is 1/12 of the shell radius, which is expected for a spherical strong shock. This holds only if N23 is still in the Sedov (adiabatic) phase. If N23 has been in the radiative phase, then the shell thickness should be smaller due to radiative cooling, and hence the plasma density would be larger than the current estimation. As a result, the cooling time scale estimated from equation (2) should be smaller, and \( t_{\text{cool}} \lesssim t_{\text{Sedov}} \). Consequently, we cannot deny the possibility that N23 has been in the radiative phase.

In summary, the age of N23 is estimated to be \( \approx 8000 \text{yr} \) from the newly discovered low-temperature component, as long as it still stays in the Sedov phase. This condition is, however, uncertain, because the discussion depends on the volume filling factor of the plasma. If, for instance, the shock propagates in the higher density ISM, N23 may have already entered into the radiative cooling phase. In this case, the remnant age estimated from the cooling timescale is smaller.

Finally, we can make an independent age estimation from the central source detected by Chandra (Hayato et al. 2006). Its luminosity is \( 1 \times 10^{34} \text{erg} \) in the 0.5–10.0 keV range.
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If the central source is a pulsar (although pulsation has not been detected), the characteristic age is \( \sim 10^3 - 10^5 \) yr (Possenti et al. 2002), which is consistent with our age estimation update.

4.3. Abundance

The main component of X-ray emission originates from the swept-up ISM in N23. Hence, the elemental abundances of N23 reflect those of its environment. Figure 4 shows the abundances obtained from the spectral analysis (table 2). The abundances of N, O, Ne, and Fe agree roughly with the LMC average (Russell & Dopita 1992). The Si and Mg abundances are smaller than those obtained (Russell & Dopita 1992), although their errors are relatively large. The Mg and Si abundances obtained by Suzaku are consistent with those from ASCA (Hughes et al. 1998), respectively, which seem to be slightly less than the LMC average.

5. Summary

We observed N23 in the Large Magellanic Cloud with Suzaku, and discovered a new soft emission component with a temperature of \( \sim 0.22 \) keV, in addition to the \( \sim 0.5-0.7 \) keV component so far known. This alters the estimate of the ionization parameter \( (n_e t) \) significantly from \( \sim 10^{10} - 10^{11} \) cm\(^{-3}\) s to \( \gtrsim 10^{12} \) cm\(^{-3}\) s. With the aid of the Chandra imaging capability, we are able to calculate the density of the plasma, and have confirmed that the supernova explosion of N23 occurred in a high-density region with an ISM density of \( \sim 4-8 \) cm\(^{-3}\). The relatively high ambient density may be related to the open cluster HS 114 (Hodge & Sexton 1966) near the remnant (Hughes et al. 2006). The parameters of the plasma from our analysis indicate that N23 is either at a late stage of the Sedov phase, nor in the radiative cooling phase. Assuming it is still in the Sedov phase, we have estimated the age of the remnant to be \( \sim 8000 \) yr from the newly discovered soft component, which is twice as old as the estimation by Hughes et al. (1998). Given the uncertainty of the volume filling factor, however, we cannot deny the possibility that N23 has already entered into the radiative phase.

The abundances of N23 are roughly consistent with the LMC average (Russell & Dopita 1992). The Si and Mg abundances obtained by spectral fitting are smaller than those obtained by Russell and Dopita (1992), although their errors on the Si and Mg abundances are relatively large. The Mg and Si abundances obtained by Suzaku are consistent with those from ASCA (Hughes et al. 1998).

We thank Dr. Y. Maeda for his useful discussion and comments. We would like to express our gratitude to all members of the Suzaku team for their contributions to the instrument preparation, spacecraft operation, software development, and in-orbit instrumental calibration. We also thank an anonymous referee for useful comments.

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