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Dynamics of X-ray–emitting ejecta in the oxygen-rich supernova remnant Puppis A revealed by the *XMM-Newton* RGS[†]

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The Galactic supernova remnant (SNR), Puppis A, is one of the brightest X-ray SNRs with energies below 1 keV. A number of oxygen-rich, fast-moving, optically emitting ejecta knots (OFMKs) are detected in this SNR. Interestingly, all these OFMKs are located in the eastern, mostly northeastern (NE) portion,[1)] whereas a neutron star is running in the opposite direction of the OFMKs[2)]. Given that this ejecta-neutron star recoil phenomenon is consistent with the recent promising supernova (SN) explosion model for explaining core-collapse SN explosions,[3)] Puppis A is an extremely important target for the study of SN explosion mechanisms.

Since significant fractions of SN ejecta are often seen only in X-rays, it is important to reveal ejecta structures in the X-ray domain. In fact, mapping observations with X-ray observatories in orbit, i.e., *XMM-Newton*, *Chandra*, and *Suzaku* have recently recognized signatures of ejecta. These ejecta are found to be localized in three locations. All of them are located in the NE quadrant, further supporting the one-sided ejection of SN debris. Interestingly, one of them showed a hint of blueshifted K-shell line emission[4)]. However, the moderate spectral resolution of these X-ray charge coupled devices (CCDs) used in the previous observations did not allow for conclusive arguments.

To reveal the precise Doppler velocities of two of the X-ray ejecta features (hereafter, the ejecta knot and the ejecta filament), we performed an *XMM-Newton* observation of Puppis A on October 20, 2012. We primarily used the Reflection Grating Spectrometer (RGS[5)]). The RGS is usually considered to be unsuitable for extended sources such as Galactic SNRs, because it is a slitless spectrometer, and hence, the extended sources suffer from energy resolution degradation. However, if the angular size of the target is sufficiently small (less than a few arc minutes) and is brighter than its surroundings, it is possible to obtain high-resolution spectra for such a target. Fortunately, our targets allow for an order-of-magnitude higher resolution spectra ($E/\Delta E \sim 150$) than nondispersive CCDs ($E/\Delta E \sim 20$).

As shown in Fig. 1, we successfully obtained a high-resolution RGS spectrum, which enabled us to reveal unambiguous Doppler velocities of 1500 ± 200 km s^{-1} (blueward) for the knot and 650 ± 130 km s^{-1} (redward) for the filament. In addition, line broadening at 654 eV (corresponding to O Lyα) is obtained to be < 0.9 eV, indicating an oxygen temperature of < 30 keV. This temperature is significantly lower than that expected ($>$100 keV) for a (collisionless) forward shock with a speed of $\sim$2000 km s^{-1} ($= 4/3$ times 1500 km s^{-1}). We showed that the low oxygen temperature can be reconciled if the ejecta knot was heated by a shock with a velocity of $\sim$600–1200 km s^{-1} and was subsequently equilibrated due to Coulomb interactions. Therefore, the ejecta knot was likely heated by a (slower) reverse shock rather than a (faster) forward shock. This result provides significant support for the idea that a reverse shock reheats the SN ejecta, which has been expected for a long time; however observational evidence is still sparse.

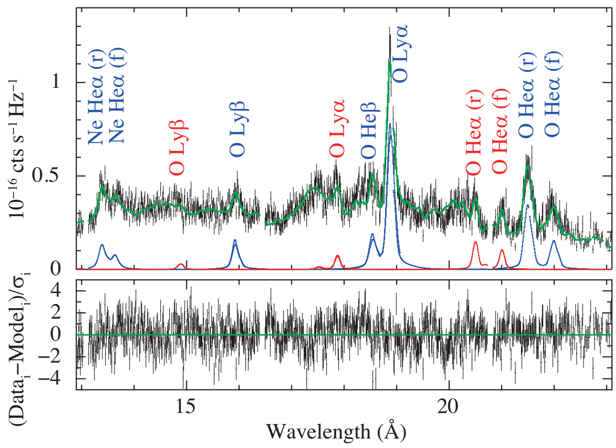

Fig. 1. *XMM-Newton*'s RGS spectrum fitted with a non-ionization equilibrium model (for diffuse background emission: Katsuda et al. 2013 for details) plus Gaussians (for the ejecta knot and ejecta filament). The best-fit models are shown in green, blue, and red for total, knot, and filament emission, respectively. The lower panel shows the residuals.

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