DYNAMICS OF X-RAY-EMITTING EJECTA IN THE OXYGEN-RICH SUPERNova REMNANT PUPPIS A REVEALED BY THE XMM-NEWTON REFLECTION GRATING SPECTROMETER

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ABSTRACT

Using the unprecedented spectral resolution of the reflection grating spectrometer (RGS) on board XMM-Newton, we reveal dynamics of X-ray-emitting ejecta in the oxygen-rich supernova remnant Puppis A. The RGS spectrum shows prominent K-shell lines, including O vii He α forbidden and resonance, O viii Lyα, O viii Lyβ, and Ne ix He α resonance, from an ejecta knot positionally coincident with an optical oxygen-rich filament (the so-called Ω filament) in the northeast of the remnant. We find that the line centroids are blueshifted by 1480 ± 60 km s$^{-1}$ (the first and second term errors are measurement and calibration uncertainties, respectively), which is fully consistent with that of the optical Ω filament. Line broadening at 654 eV (corresponding to O viii Lyα) is obtained to be $\sigma \gtrsim 0.9$ eV, indicating an oxygen temperature of $\lesssim 30$ keV. Analysis of XMM-Newton MOS spectra shows an electron temperature of $\sim 0.8$ keV and an ionization timescale of $\sim 2 \times 10^{10}$ cm$^{-3}$ s. We show that the oxygen and electron temperatures as well as the ionization timescale can be reconciled if the ejecta knot was heated by a collisionless shock whose velocity is $\sim 600$–1200 km s$^{-1}$ and was subsequently equilibrated due to Coulomb interactions. The RGS spectrum also shows relatively weak K-shell lines of another ejecta feature located near the northeastern edge of the remnant, from which we measure redward Doppler velocities of $650 \pm 70$ km s$^{-1}$.

Key words: ISM: abundances – ISM: individual objects (Puppis A) – ISM: supernova remnants – X-rays: ISM

Online-only material: color figures

1. INTRODUCTION

The Galactic supernova remnant (SNR) Puppis A is one of the so-called oxygen-rich SNRs, in which oxygen-rich fast-moving optically emitting ejecta knots (OFMKs) are identified. So far, eight other SNRs, Cas A and G292.0+1.8 in our Galaxy and six others in the Magellanic Clouds and NGC 4449, are categorized in this class (see Vink 2012 for a recent summary). Of these, Puppis A is particularly interesting because all of the OFMKs are located in the eastern and northeastern (NE) portion (Winkler & Kirshner 1985; Winkler et al. 1988), while the stellar remnant is moving in the opposite southwestern direction (Petre et al. 1996; Hui & Becker 2006; Winkler & Petre 2007; Becker et al. 2012). This is consistent with recent models, which predict that SN ejecta are expelled preferentially in one direction, while the stellar remnant receives a kick in the opposite direction (Wongwathanarat et al. 2013 and references therein). Thus, Puppis A is an extremely important target for the study of SN explosion mechanisms as well as SN nucleosynthesis.

Puppis A is one of the brightest SNRs in the X-ray sky. The X-ray emission has been thought to be dominated by strong cloud–shock interactions (Charles et al. 1978; Petre et al. 1982, references therein). A large area of the remnant was previously mapped by X-ray observatories in orbit, i.e., XMM-Newton, Chandra, and Suzaku. They confirmed earlier results that the X-ray emission is dominated by the swept-up interstellar medium (Hwang et al. 2005, 2008; Katsuda et al. 2010). On the other hand, the data also revealed signatures of SN ejecta in three locations: a Si-rich clump (Hwang et al. 2008), a bright O-Ne-Mg-(Si-S)-rich knot (called the ejecta knot hereafter; Katsuda et al. 2008), whose southern portion is positionally coincident with an “Ω”-shaped OFMK (the so-called Ω filament named by Winkler & Kirshner 1985), and an O-Ne-Mg-rich filament (called the ejecta filament hereafter; Katsuda et al. 2010). All of them are located in the NE quadrant, further supporting the one-sided ejection of SN debris.

While picking up ejecta features reveals two-dimensional ejecta distributions on the plane of the sky, measurements of Doppler velocities can provide us with line-of-sight structures (see Dewey 2010 for a recent review of kinematics of X-ray SNRs). Katsuda et al. (2008) found that the ejecta knot described above shows blueshifted K-shell lines. The Doppler velocities were measured to be $3400^{+1000}_{-800}$ km s$^{-1}$ at the northern knot and $1700^{+700}_{-800}$ km s$^{-1}$ at the southern knot which agrees with the optical measurement of $\sim 1500$ km s$^{-1}$ (Winkler & Kirshner 1985). The possible different Doppler velocities between the north and the south led us to suggest that the ejecta knot actually consists of two different knots that appear to be located close to each other. However, the poor quality of the data prevented us from making strong arguments; the X-ray data were taken by the XMM-Newton European Photon Imaging Camera (EPIC; Turner et al. 2001; Strüder et al. 2001) with moderate spectral resolution ($E/\Delta E \sim 20$), and also the ejecta knot was detected at the edge of the field of view (FOV) where calibration uncertainties would be large.

Here, we report on precise Doppler measurements for the ejecta knot and the ejecta filament in Puppis A based on the unprecedented spectral resolution X-ray spectra ($E/\Delta E \sim 150$)
obtained by the reflection grating spectrometer (RGS; den Herder et al. 2001) on board XMM-Newton. In addition, we give a restrictive upper limit on an oxygen temperature of the ejecta knot for the first time. These new measurements allow us to discuss the nature of the ejecta knot in detail.

2. OBSERVATION AND DATA REDUCTION

We performed an XMM-Newton observation of Puppis A on 2012 October 20 (Obs.ID 0690700201), aiming at the fast-moving ejecta knot coincident with the optical Ω filament. Our primary instrument in this observation is the RGS that can produce high-resolution X-ray spectra, while we also make use of the EPIC data to support the RGS results as well as to obtain additional information. The dispersion direction of the RGS is 96.4 measured east from north, as we show in Figure 1 (left)—an X-ray image of Puppis A generated by existing XMM-Newton and Chandra data. Fortunately, no background flare is seen in our light curve, allowing us to use full exposure times of 20.8 ks, 12.1 ks, and 11.7 ks for the RGS1/2, MOS1, and MOS2, respectively. All the raw data were processed using version 11.0.0 of the XMM Science Analysis Software and the calibration data files available in 2012 May.

3. RGS SPECTRA

The slitless RGS spectrometer is generally not useful for extended sources like Puppis A because off-axis emission along the dispersion direction is detected at wavelength positions shifted with respect to the on-axis source, which causes degradation of energy resolution. However, if the angular size of the target is small enough (≤ a few arcminutes) and is brighter than its surroundings, it is possible to obtain high-resolution spectra than nondispersive CCDs. There is another ejecta feature, i.e., the ejecta filament described in Section 1, within the RGS FOV. Since the angular size of the filament along the dispersion direction is as thin as 1′, we can also find its signatures in the RGS spectrum. The two ejecta features of interest are indicated on a Chandra image shown in Figure 1 (right).

The analysis method basically follows that in our previous work (Katsuda et al. 2012). Briefly, we first extract four RGS spectra from 0.8 width sectors along the cross-dispersion direction. We then smooth the RGS response designed for on-axis point sources, based on emission profiles along the dispersion direction by using the rgsrmfsmooth software. Finally, we fit the RGS spectrum with emission models in the XSPEC package (Arnaud 1996). The RGS background (BG) is generated from a blank-sky observation (Lockman hole: Obs.ID 0147511601), as we did in our previous work. The blank-sky BG emission is less than 1% of the source emission in the energy band analyzed.

Here, the RGS response in each region is smoothed with three distinct emission profiles responsible for (1) the ejecta knot, (2) the ejecta filament, and (3) their surrounding diffuse emission, so that we can derive physical parameters for individual features. Emission profiles are generated with either the Chandra or XMM-Newton image, for which we take account of vignetting effects of XMM-Newton’s X-ray telescope and the asymmetry of the effective area along the dispersion axis described in the literature (Broersen et al. 2013). The emission profiles for the ejecta features are extracted from Chandra images masked for them, for which we subtract underlying diffuse emission by interpolating the surrounding diffuse emission. We have checked that, even if we change the intensity of underlying diffuse emission by ±20% which is a small-scale inhomogeneity around the ejecta knot, the fit results presented below are not affected significantly. Figure 2 shows the X-ray emission profiles in 0.6–0.7 keV for the four regions. The three profiles in each panel are responsible for (1) the ejecta knot in blue, (2) the ejecta filament in red, and (3) the surroundings in black.

Figures 3 and 4 show BG-subtracted RGS1 and RGS2 spectra for the four regions. While most of the emission is due to overall diffuse emission which acts as effective BG emission in our analysis, several peaks can be identified as line emission from our two interesting ejecta features. Some of them are indicated in the plot as blue and red labels for the ejecta knot and the ejecta filament, respectively. Note that there are large wavelength shifts in line centroids between the knot (blue) and the filament (red) by about 1 Å. This is mainly due to the off-axis position (about 8′) of the filament; an offset of 1′ causes a wavelength shift of 0.138 Å. We use data in the energy range of 0.5–1 keV (24–13 Å) where line emission from the ejecta features are
clearly detected. Dividing the energy band into four sections (0.5–0.6 keV, 0.6–0.7 keV, 0.7–0.85 keV, and 0.85–0.97 keV), we generate RGS responses using the same energy-band images. We note that the available energy ranges for the RGS1 and RGS2 are limited to 0.5–0.8 (24–15.5 Å) and 0.65–1 keV (19–13 Å), respectively, since chip 7 in the RGS1 and chip 4 in the RGS2 are no longer operating.

The RGS spectra consist of diffuse emission and emission from the ejecta knot and ejecta filament. We model the diffuse emission and the ejecta in terms of a nonequilibrium ionization shock model (the vrshock model; Borkowski et al. 2001) and individual Gaussian components, respectively. We use nine Gaussian components for the ejecta knot and six for the ejecta filament. We impose the Gaussians in the knot component to be O vii Heα forbidden at 0.561 keV (22.1 Å), O vii Heα intercombination at 0.568 keV (21.8 Å), O vii Heβ resonance at 0.574 keV (21.6 Å), O vii Lyα at 0.654 keV (19.0 Å), O vii Heβ at 0.666 keV (18.6 Å), O vii Lyβ at 0.775 keV (16.0 Å), Ne ix Heα forbidden at 0.905 keV (13.7 Å), and Ne ix Heβ intercombination at 0.915 keV (13.6 Å). The six Gaussians for the filament component are the same O K-shell lines listed above. For the diffuse component, the degradation of RGS spectra is severe owing to the large spatial extent; the effective systematic uncertainties in our measurements and also see if energy dependence is present; the RGS1 covers 0.5–0.8 keV including O K-shell lines while the RGS2 covers 0.65–1 keV including O and Ne K-shell lines, respectively. Before BG subtraction, each spectrum is grouped into bins with at least ~25 counts, which allows us to perform a χ² test.

With this fitting strategy, we obtain fairly good fits for all the spectra as shown in Figure 3, where individual knot and filament components are shown in blue and red, respectively, as well as the total model in green. The fit results are summarized in Table 1. Overall, the redshifts and line broadening derived from the RGS1 and the RGS2 are consistent with each other, suggesting no significant energy dependence for these parameters. We also fitted the RGS2 spectra, by using a specific energy band for Ne ix Heα lines, finding consistent results as in Table 1. Figure 4 shows close-up RGS spectra for O K-shell lines. In this plot, we show the best-fit models shifted at rest-frame positions (i.e., redshift = 0) in green. The Doppler shifts of the ejecta knot are clearly seen.

The blueshift measured at the southernmost region (region D), 1560 ± 60 km s⁻¹, is consistent with our previous X-ray measurements (Katsuda et al. 2008), significantly reducing the uncertainty. It also matches with the previous optical measurements for the Ω filament: 1520 ± 40 km s⁻¹ or 1570 ± 20 km s⁻¹ from the SIT or CCD spectrum, respectively (Winkler & Kirshner 1985). While the blueshifts in the four regions are all close to each other, that in the northernmost region is slightly slower than those in the other regions. This conflicts with our previous measurements which suggested a faster velocity in the north of the knot than that in the south. Given much improved spectral resolution in the current data, we believe that the result presented here is more reliable than the previous one. As for the slightly slower velocity, it may indicate that the northern part is responsible for a tail structure delayed from the main body of the ejecta knot. We find, for the first time, that line emission from the filament is redshifted by ~650 km s⁻¹.

Line broadening in the ejecta knot is found to be fairly narrow. It ranges from 0 to 0.9 eV at 0.654 keV in the four regions, which we take as our measurement uncertainty. Based on the relation between temperatures and line broadening, σ = E₀ν/√kT/mc² (Rybicki & Lightman 1979), we obtain an upper limit for the oxygen temperature of 30 keV.

Line intensity ratios measured are consistent with those expected by a non-equilibrium ionization plasma model. We have indeed confirmed that the vne model (Borkowski et al. 2001) can also well reproduce the RGS spectra (values of χ²/dof range from 1.4 to 1.6) with plausible electron temperatures, ~0.4–1 keV, an ionization timescale of 2 × 10¹⁰ cm⁻³ s⁻¹, and both Doppler shifts and line broadening consistent with those in Table 1.

4. MOS SPECTRA

Since the RGS spectra are heavily contaminated by the surrounding diffuse emission in our case, electron temperatures and ionization timescales for our interesting features are better
Figure 3. *XMM-Newton* spectra of the four regions in Figure 1. The RGS1 and RGS2 cover 15.5–24 Å (∼0.8–0.51 keV) and 13–19.1 Å (∼1–0.65 keV), respectively.

The two (RGS1 and RGS2) data sets are simultaneously fitted with a combination model of $v_{\text{pshock}}$ (for diffuse background emission) + nine Gaussians (for the ejecta knot) + six Gaussians (for the ejecta filament). The total best-fit model is shown in green, while individual components are in blue and red for the ejecta knot and the ejecta filament, respectively. Lower panels show the residuals.

It is difficult to measure absolute (relative to hydrogen) metal abundances for metal-rich plasmas because continuum emission comes from the metals themselves and no longer reflects the amount of hydrogen, and also because in our case the continuum emission from the ejecta knot is difficult to estimate adequately given that a considerable fraction of the X-ray emission is due to local BG that cannot be subtracted perfectly. Therefore, in our spectral modeling, we examine two abundance patterns. In case A, we assume the Fe/H abundance to be the solar value (Anders & Grevesse 1989) as line emission from Fe is not evident in our X-ray spectra, while in case B, we assume the O/H abundance to be 2000 times the solar value which is derived from optical spectroscopy of the Ω filament (Winkler & Kirshner 1985). We find that the $v_{\text{nei}}$ model represents the data fairly well for both of the two cases. The best-fit models presented in Figure 6 are those for case A which gives slightly better fits than case B.

Table 2 summarizes the results and notes details of our fitting.

The blueshifts from the MOS spectra are in reasonable agreement with the RGS measurements considering the relatively large calibration uncertainty (±5 eV) on the energy scale of the MOS. We also confirm the elevated abundances of O, Ne, and Mg compared with Fe. On the other hand, the electron temperatures and ionization timescales are outside statistical uncertainties of our previous measurements (Katsuda et al. 2008).
Figure 4. Close-up RGS spectra for O K-shell lines. To clarify the Doppler shifts of the two ejecta features, we here show the best-fit models shifted at rest-frame positions, i.e., redshift = 0. The lower panels show residuals. Blueshifts for O Lyα and O Heα for the ejecta knot component are clearly seen.

The discrepancy would be partly due to the different data quality; the data were taken at the edge (previous) or center (this time) of the FOV, and partly due to the different fitting strategy; here we use (1) the most recent version of the vnei code, (2) different spectral extraction regions, and (3) different energy bands, and also we fix $N_{\text{H}}$ to be $3 \times 10^{21} \, \text{cm}^{-2}$ (Katsuda et al. 2010), but allow abundances of C and N to vary freely. Not only these analysis improvements but also the fact that blueshifts derived here are closer to the RGS measurements assure reliability of the current results rather than the previous ones.

Assuming the plasma depths to be 1′ (or $\sim 0.6$ pc at a distance of 2.2 kpc; Reynoso et al. 2003), which is roughly the size of the knot, we calculate densities and masses in each region. Although it is often assumed that a density ratio between electrons and protons to be unity or so, this assumption is incorrect for supermetal rich plasmas like the ejecta knot in Puppis A. Therefore, we here calculate the ratio, taking account of abundances as well as ion fractions based on the SPEX code (Kaastra et al. 1996).

Then, the emission measures and abundances give densities and masses for each species as summarized in Table 3. The total mass in each region, $\sim 0.01 \, M_{\odot}$, is consistent with our previous estimates (Katsuda et al. 2008), and is comparable with typical OFMKs in the remnant (Winkler et al. 1988).

5. DISCUSSION

The XMM-Newton RGS allowed successful measurements of accurate Doppler velocities of two X-ray-emitting ejecta features (i.e., the ejecta knot and the ejecta filament) in the NE quadrant of Puppis A. In our spectral analysis, we divided each feature into four cross-dispersion regions. The error-weighted mean Doppler velocities for the four regions are obtained to be $1480 \pm 140 \pm 60 \, \text{km} \, \text{s}^{-1}$ blueward for the ejecta knot and $650 \pm 70 \pm 60 \, \text{km} \, \text{s}^{-1}$ redward for the ejecta filament, where the first and second term errors, respectively, represent the standard deviation for the four regions and a wavelength accuracy of the
Table 1

| Component | Parameter | A | B | C | D |
|-----------|-----------|---|---|---|---|
| Knot      | Redshift ($10^{-3}$) | $-4.5^{+0.3}_{-0.1}$ to $-4.1^{+0.1}_{-0.0}$ | $-5.0^{+0.2}_{-0.2}$ to $-4.6^{+0.2}_{-0.2}$ | $-5.3^{+0.3}_{-0.1}$ to $-5.3^{+0.3}_{-0.1}$ | $-5.2^{+0.2}_{-0.2}$ |
|           | Line broadening (σ in eV at 0.654 keV) | 0.01 (<0.4), 0.0 (<0.7) | 0.3<4.0<2.9 | 0.01 (<0.4), 0.0 (<0.4) | 0.8 < 0.3 |
|           | Intensities: O He (i) | 411 ± 101 | 812 ± 123 | 882 ± 126 | 657 ± 104 |
|           | O He (i) | 4 ± 87 | 0 (<49) | 113 ± 104 | 0 (<74) |
|           | O He (r) | 702 ± 103 | 1623 ± 133 | 1519 ± 127 | 1085 ± 116 |
|           | O Heβ | 157 ± 30 | 342 ± 38 | 428 ± 40 | 134 ± 33 |
|           | O Lyα | 956 ± 54 | 1898 ± 64 | 863 ± 52 | 220 ± 37 |
|           | O Lyβ | 123 ± 20 | 247 ± 24 | 107 ± 21 | 40 ± 16 |
|           | Ne He (i) | 26 ± 25 | 119 ± 29 | 139 ± 28 | 48 ± 22 |
|           | Ne He (r) | 0 (<6) | 25 (<54) | 42 ± 28 | 9 (<30) |
|           | Ne He (r) | 149 ± 25 | 216 ± 29 | 191 ± 28 | 47 ± 22 |
| Filament  | Redshift ($10^{-3}$) | 2.3<0.2 | 1.9<0.1 | 2.2<0.1 | 2.4<0.4 |
|           | Intensities: O He (i) | 285 ± 112 | 489 ± 118 | 374 ± 123 | 207 ± 179 |
|           | O He (i) | 0 (<48) | 77 (<185) | 70 (<167) | 129 ± 104 |
|           | O He (r) | 459 ± 101 | 612 ± 109 | 1069 ± 119 | 619 ± 117 |
|           | O Heβ | 26 (<63) | 28 (<69) | 213 ± 38 | 366 ± 43 |
|           | O Lyα | 237 ± 41 | 167 ± 40 | 210 ± 38 | 223 ± 40 |
|           | O Lyβ | 113 ± 35 | 56 ± 34 | 0 (<34) | 0 (<7) |
| Diffuse    | $kT_e$ (keV) | 0.46 ± 0.01 | 0.47 ± 0.01 | 0.44 ± 0.01 | 0.45 ± 0.01 |
|            | $\chi^2$/dof | 1937.8/1260 | 2073.0/1280 | 1841.6/1260 | 1875.9/1257 |

Notes. N_H values are fixed to 3 × 10^{21} cm^{-2}. Line intensities are in units of 10^{-5} photons cm^{-2} s^{-1}, respectively. Two values of the redshifts and line broadening in Regions A, B, and C are derived by the RGS1 (left) and the RGS2 (right). The errors represent 90% confidence levels on an interesting single parameter.

Table 2

| Parameter | Case A | Case B | Case A | Case B | Case A | Case B |
|-----------|--------|--------|--------|--------|--------|--------|
| $kT_e$ (keV) | 0.93^{+0.15}_{-0.12} | 1.03 ± 0.12 | 0.89^{+0.09}_{-0.05} | 0.83^{+0.06}_{-0.12} | 0.63^{+0.13}_{-0.08} | 0.63^{+0.16}_{-0.08} |
| log(n_e kpc^{-1} cm^{-3} s) | 10.4^{+0.09}_{-0.06} | 10.4^{+0.07}_{-0.06} | 10.2^{+0.13}_{-0.07} | 10.2^{+0.07}_{-0.02} | 10.2^{+0.09}_{-0.06} | 10.2^{+0.09}_{-0.11} |
| C/H/O | 11.9^{+0.0}_{-0.7} | 6000^{+1200}_{-3800} | 5.6^{+0.2}_{-0.6} | 1800 ± 1800 | 3.1^{+3.6}_{-1.2} | 1500 ± 1300 |
| N/H/O | 0.0 (<1.2) | 0 (<300) | 1.8 (<3.8) | 500 (<1100) | 1.5^{+1.4}_{-1.1} | 700 ± 500 |
| O/H/O | 5.2^{+1.4}_{-0.8} | 2000^{a} | 6.9^{+1.1}_{-0.8} | 200^{a} | 4.5^{+1.1}_{-0.8} | 2000^{a} |
| Ne/H/O | 6.5^{+1.4}_{-1.1} | 2400^{+100}_{-200} | 10.3^{+1.4}_{-2} | 3000 ± 200 | 7.2^{+2.2}_{-1.7} | 3400 ± 300 |
| Mg/H/O | 5.6^{+1.0}_{-0.9} | 2100 ± 200 | 7.9^{+1.2}_{-1.2} | 2300 ± 200 | 7.2^{+1.9}_{-1.8} | 3200 ± 500 |
| Si/H/O | 3.2 ± 0.7 | 1200^{+100}_{200} | 2.8^{+1.2}_{-1.1} | 900 ± 300 | 4.0^{+1.4}_{-1.0} | 1900^{+400}_{-500} |
| Fe/H/O | 1^{a} | 380^{+70}_{-40} | 1^{a} | 270^{+90}_{-110} | 1^{a} | 390^{+150}_{-110} |
| Redshift ($10^{-3}$) | $-6.6^{+0.6}_{-0.1}$ | $-6.6^{+0.6}_{-0.1}$ | $-6.1^{+0.3}_{-0.1}$ | $-6.1^{+0.3}_{-0.1}$ | $-5.4^{+1.6}_{-0.1}$ | $-5.4^{+1.0}_{-0.1}$ |
| $n_e m_H V/4\pi d^2$ (10^3 cm^{-3}) | 740^{+130}_{-160} | 1.84^{+0.17}_{-0.29} | 240^{+60}_{-10} | 0.89^{+0.07}_{-0.04} | 460^{+170}_{-160} | 1.04^{+0.15}_{-0.18} |
| $\chi^2$/dof | 187.7/126 | 200.6/126 | 141.0/103 | 148.3/103 | 180.8/108 | 192.1/108 |

Note. 4 (Fe/H)/(Fe/H)_{O} and (O/H)/(O/H)_{O} are fixed to 1 (Case A) and 2000 (Case B), respectively. N_H values are fixed to 3 × 10^{21} cm^{-2}. The errors represent 90% confidence levels.

RGS. The Doppler velocity of the ejecta knot is fully consistent with previous optical measurements for the Ω filament (Winkler & Kirshner 1985), ensuring robustness of our measurements. The RGS spectra also enabled, for the first time, to measure broadening of O and Ne K-shell lines of the ejecta knot. The broadening is found to be modest, $\sigma \lesssim 0.9$ eV at O VIII Lyα, indicating an upper limit of an oxygen temperature of 30 keV. As far as we know, this is the second result that we were able to measure an oxygen temperature of fast-moving ejecta knots in X-rays. Comparing our results with the first successful object, a comparably fast-moving ejecta knot in the northwestern rim of SN 1006, we notice that the oxygen temperature in Puppis A’s knot is at least an order of magnitude lower than that in SN 1006’s knot ($kT_{O} \sim 300$ keV; Vink et al. 2003; Broersen et al. 2013).

The post-shock temperature, $T_{s}$, for species $i$ with mass $m_{i}$ right behind a collisionless shock in the absence of the magnetic pressure is given as (e.g., Spitzer 1965):

$$kT_{s} = \frac{3}{16} m_{i} v_{sh}^{2}$$

(1)

for shock velocity, $v_{sh}$. Thus, the particles will have mass-proportional temperatures in the limit of collisionless plasma.
is similar to the gas velocity: \( \sim \) respectively.

The lower panels are the residuals for north, west, and south from top to bottom, expected to be \( \sim \) low electron temperature of \( \sim 1.5 \) keV in SN 1006 has been measured, \( \sim 30 \) keV. The deviation may be due to plasma processes that raise an electron temperature at (in front of) the shock (Ohira et al. 2008; Rakowski et al. 2008) and/or significant energy leakage into cosmic rays that lowers post-shock temperatures of all particle species (Hughes et al. 2000; Helder et al. 2009). In any case, oxygen can have a lower temperature than that predicted by Equation (1).

In this context, it is important to clarify whether the \( T_O/T_e \) ratio observed in Puppis A’s knot can be explained by temperature equilibration due to Coulomb interactions behind a collisionless shock or requires other scenarios. To this end, assuming pure collisionless shock heating, i.e., initial temperatures are given by Equation (1), we solve the following temperature equilibration due to Coulomb interactions (e.g., Spitzer 1965):

\[
\frac{dT_i}{dt} = \frac{T_j - T_i}{t_{eq(i,j)}} = \frac{5.87}{n_j Z_i^2 Z_j^2 \ln(A)} \left( \frac{T_i}{A_i} + \frac{T_j}{A_j} \right)^2
\]

for species \( i \) and \( j \) with atomic numbers \( A_i \) and \( A_j \), charges \( Z_i \) and \( Z_j \), number density \( n_j \), and the Coulomb logarithm \( \ln(A) \sim 40 \).

We coupled the differential equations for electrons, protons, He, C, O, Ne, Mg, Si, and Fe, using the abundances for either case A (He/H = 1, C/H = O/H = 5, Ne/H = 8, Mg/H = 7, Si/H = 3, and Fe/H = 1 times the solar values, see Table 2) or case B (He/H = 1, C/H = O/H = 2000, Ne/H = 3000, Mg/H = 2500, Si/H = 1000, and Fe/H = 300 times the solar values). After examining several shock velocities, we find that the electron temperatures and ionization timescales in the ejecta knot can be best explained at \( v_{sh} \sim 1200 \) km s\(^{-1}\) or \( v_{sh} \sim 600 \) km s\(^{-1}\) for case A or case B, respectively. The temperature histories for electrons, protons, and oxygen as a function of \( n_i \) are shown in Figure 7. From the plot, we also find that the oxygen temperature measured, \( kT_O \lesssim 30 \) keV, is consistent with the expectation in both cases. Therefore, we do not need to invoke some exotic scenarios explain the low \( T_O/T_e \) ratio.

Still, the temperatures measured may be also reproduced for the case that initial post-shock temperatures are not proportional to the post-shock electron and proton temperatures. In this context, it is important to clarify whether the \( T_O/T_e \) ratio observed in Puppis A’s knot can be explained by temperature equilibration due to Coulomb interactions behind a collisionless shock or requires other scenarios. To this end, assuming pure collisionless shock heating, i.e., initial temperatures are given by Equation (1), we solve the following temperature equilibration due to Coulomb interactions (e.g., Spitzer 1965):

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\]

for species \( i \) and \( j \) with atomic numbers \( A_i \) and \( A_j \), charges \( Z_i \) and \( Z_j \), number density \( n_j \), and the Coulomb logarithm \( \ln(A) \sim 40 \).

We coupled the differential equations for electrons, protons, He, C, O, Ne, Mg, Si, and Fe, using the abundances for either case A (He/H = 1, C/H = O/H = 5, Ne/H = 8, Mg/H = 7, Si/H = 3, and Fe/H = 1 times the solar values, see Table 2) or case B (He/H = 1, C/H = O/H = 2000, Ne/H = 3000, Mg/H = 2500, Si/H = 1000, and Fe/H = 300 times the solar values). After examining several shock velocities, we find that the electron temperatures and ionization timescales in the ejecta knot can be best explained at \( v_{sh} \sim 1200 \) km s\(^{-1}\) or \( v_{sh} \sim 600 \) km s\(^{-1}\) for case A or case B, respectively. The temperature histories for electrons, protons, and oxygen as a function of \( n_i \) are shown in Figure 7. From the plot, we also find that the oxygen temperature measured, \( kT_O \lesssim 30 \) keV, is consistent with the expectation in both cases. Therefore, we do not need to invoke some exotic scenarios explain the low \( T_O/T_e \) ratio.

Still, the temperatures measured may be also reproduced for the case that initial post-shock temperatures are not proportional

### Table 3

| Parameter | Case A | Case B | Case A | Case B | Case A | Case B |
|-----------|--------|--------|--------|--------|--------|--------|
| \( n_e \) | 44000  | 11000  | 33000  | 7800  | 37000  | 7200  |
| \( n_1 \) | 35000  | 3600   | 26000  | 3700  | 29000  | 3400  |
| \( n_C \) | 150    | 770    | 53     | 240   | 33     | 190   |
| \( n_N \) | 150    | 610    | 150    | 620   | 110    | 570   |
| \( n_{Ne} \) | 28 | 110 | 33 | 130 | 27 | 140 |
| \( n_{Mg} \) | 7.5 | 28 | 7.7 | 31 | 8.1 | 41 |
| \( n_{Si} \) | 4.0 | 15 | 2.6 | 11 | 4.2 | 23 |
| \( n_{Fe} \) | 1.6 | 6.3 | 1.2 | 4.7 | 1.4 | 6.2 |
| \( M_4 \) | 82 | 0.8 | 36 | 0.5 | 62 | 0.7 |
| \( M_C \) | 4.3 | 22 | 14 | 4.0 | 0.8 | 4.7 |
| \( M_O \) | 5.8 | 23 | 3.3 | 14 | 3.8 | 19 |
| \( M_{Ne} \) | 1.3 | 5.0 | 0.9 | 3.7 | 1.1 | 5.9 |
| \( M_{Mg} \) | 0.4 | 1.6 | 0.3 | 1.0 | 0.4 | 2.1 |
| \( M_{Si} \) | 0.3 | 1.0 | 0.1 | 0.4 | 0.2 | 1.3 |
| \( M_{Fe} \) | 0.2 | 0.8 | 0.1 | 0.4 | 0.2 | 0.7 |

**Note.** Typical errors which are mainly due to the assumption of the plasma depth are about a factor of two.
to particle masses, as is often observed. If it is the case, the shock velocities would be different, causing uncertainties on the shock velocity. Recent observational studies agree in that the initial electron-to-proton temperature ratio, $T_e/T_p = \beta$, is close to unity (full equilibration) for slow shocks ($v_{sh} \lesssim 400 \text{ km s}^{-1}$), but gradually decreases for faster shocks (Ghavamian et al. 2007; Heng 2010, and references therein). We take the value of $\beta$ to be 0.2 which is typical around $v_{sh} = 1000 \text{ km s}^{-1}$ (van Adelsberg et al. 2008). We find that temperature histories expected at $v_{sh} \sim 1000 \text{ km s}^{-1}$ (case A) or $v_{sh} \sim 600 \text{ km s}^{-1}$ (case B), indicated as dotted lines in Figure 7, best match our measurements. In this context, we argue that the shock velocity does not depend on the degree of initial temperature equilibration compared with the ambiguity of abundances.

It is interesting to note that the inferred shock velocity, 600–1200 km s$^{-1}$, is less than the shocked-gas velocity, $\sim 2000 \text{ km s}^{-1}$. This suggests that the ejecta knot was heated by a reverse shock rather than a forward shock, since the forward shock velocity should be $\sim 2500 \text{ km s}^{-1}$ according to the Rankine–Hugoniot relation:

$$v_{fs} = \frac{\gamma + 1}{2} v_{sg},$$  \hspace{1cm} (3)

where $v_{fs}$ and $v_{sg}$ are velocities of the forward shock and the shocked gas, respectively, and $\gamma$ is the specific heat ratio taken to be 5/3 for a non-relativistic ideal gas. The Rankine–Hugoniot relation over the reverse shock can be written down as:

$$v_{free} - v_{rs} = \frac{\gamma + 1}{\gamma - 1} (v_{sg} - v_{rs}),$$  \hspace{1cm} (4)

where $v_{free}$ and $v_{rs}$ are velocities of the freely-expanding ejecta and the reverse shock in the observer’s frame. Substituting $v_{free} - v_{rs}(=v_{sh}) = 600–1200 \text{ km s}^{-1}$, $v_{sg} = 2000 \text{ km s}^{-1}$, and $\gamma = 5/3$, we compute the value of $v_{free}$ to be $2900–2450 \text{ km s}^{-1}$, depending on the shock velocity of $600–1200 \text{ km s}^{-1}$. This velocity agrees with a typical ejecta velocity in the O-rich layer for a Type Iib SN (Houck & Fransson 1996; Iwamoto et al. 1997) which is likely the origin of Puppis A (Chevalier 2005). Also, the distance, 0.3–0.6 pc, that the shock of this velocity travels for $\sim 500$ years (which is a product of the ionization timescale, $3 \times 10^{10} \text{ cm}^{-3} \text{s}$, divided by the electron density, $2 \text{ cm}^{-3}$, as in Tables 2 and 3) is comparable to the size of the knot ($\sim 0.6 \text{ pc}$), showing self-consistency of our interpretation.

We comment on the remarkable difference in $T_0/T_e$ between Puppis A’s knot and SN 1006’s knot. The proper motion of SN 1006’s knot is measured from recent X-ray observations to be $\sim 3000 \text{ km s}^{-1}$ (Katsuda et al. 2013). Provided that it is shocked by a forward shock, then the shock velocity would be the proper motion itself. On the other hand, if it is shocked by a reverse shock, the proper motion should be the velocity of the shocked gas. Also, freely expanding ejecta velocities are likely $\sim 10000 \text{ km s}^{-1}$ (Iwamoto et al. 1999), since there is a general consensus that SN 1006 is a Type Ia SNR. This is indeed comparable to a freely expanding Si-rich ejecta velocity of $\sim 7000 \text{ km s}^{-1}$ measured by the UV absorption edge (Hamilton et al. 2007) as well as a simple estimate from the radius at the knot ($\sim 9 \text{ pc}$) and the SNR age ($\sim 1000 \text{ yr}$). Then, Equation (4) gives the reverse shock velocity in the ejecta-rest frame to be $\sim 9300 \text{ km s}^{-1}$ (or $\sim 5300 \text{ km s}^{-1}$, if we take $v_{free}$ to be $7000 \text{ km s}^{-1}$). Therefore, the shock velocities estimated for SN 1006’s knot are at least a few times faster than that for Puppis A’s knot. In addition, the ionization timescale is an order-of-magnitude lower in SN 1006’s knot than in Puppis A’s knot. These differences can qualitatively explain the different oxygen temperatures.

Future high-resolution X-ray spectroscopy with the nondispersive soft X-ray spectrometer on board $Astro-H$ (FWHM $\sim 5 \text{ eV}$; Takahashi et al. 2010; Mitsuda et al. 2010) will reveal ion and electron temperatures for many SNRs. Hopefully, we will be able to measure ion temperatures in different ionization states for every species. Such information will significantly improve our understanding of temperature equilibration for fast...
collisionless shocks. One particularly interesting target in Puppis A would be the Si-rich clump in the NE remnant (Hwang et al. 2008), for which the RGS cannot produce high-resolution spectra due to its large angular size (3′ × 5′). Fortunately, this target is scheduled to be observed in 2013 January with a soft X-ray spectrometer on board the Micro-X sounding rocket experiment8 (FWHM ∼ 2 eV; Figueroa-Feliciano et al. 2012). This experiment will provide exciting results shortly.

6. SUMMARY

We have presented results from our new XMM-Newton RGS and MOS observations of two ejecta features in the Galactic SNR Puppis A: one is an ejecta knot positioned coincident with the optical Ω filament (Winkler & Kirshner 1985), and the other is an ejecta filament located near the NE edge of the remnant. The results obtained are summarized below.

1. The Doppler velocity of the ejecta knot is measured to be 1480 ± 140 ± 60 km s⁻¹ blueward, which is fully consistent with previous optical measurements for the Ω filament (Winkler & Kirshner 1985). We find that the Doppler velocities are constant within the knot, except for a northermost piece where a slightly slower velocity is indicated.

2. An upper limit of line broadening for O K-shell lines in the ejecta knot is obtained to be ~0.9 eV, leading to an oxygen temperature of ≤30 keV. This upper limit, combined with the electron temperature and the ionization timescale derived from the MOS spectra, suggests that the ejecta knot was heated by a reverse shock whose velocity is ~600–1200 km s⁻¹, without requiring rapid temperature equilibration due to plasma instabilities or temperature dropping due to energy leakage into cosmic rays.

3. The oxygen temperature of the ejecta knot is an order-of-magnitude lower than that obtained in a comparably fast-moving ejecta knot in SN 1006 (Vink et al. 2003; Broersen et al. 2013). We argue that the difference would be due to both different shock velocities and the ionization timescale.

4. The Doppler velocity for the ejecta filament is also measured, for the first time, to be 650 ± 70 ± 60 km s⁻¹ redward.

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