Integral Field Spectroscopy of Supernova Remnant 1E0102–7219 Reveals Fast-moving Hydrogen and Sulfur-rich Ejecta

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Abstract

We study the optical emission from heavy element ejecta in the oxygen-rich young supernova remnant 1E 0102.2–7219 (1E 0102) in the Small Magellanic Cloud. We have used the Multi-Unit Spectroscopic Explorer optical integral field spectrograph at the Very Large Telescope on Cerro Paranal and the wide field spectrograph (WiFeS) at the ANU 2.3 m telescope at Siding Spring Observatory to obtain deep observations of 1E 0102. Our observations cover the entire extent of the remnant from below 3500 Å to 9350 Å. Our observations unambiguously reveal the presence of fast-moving ejecta emitting in [S II], [S III], [Ar III], and [Cl II]. The sulfur-rich ejecta appear more asymmetrically distributed compared to oxygen or neon, a product of carbon burning. In addition to the forbidden line emission from products of oxygen burning (S, Ar, Cl), we have also discovered Hα and Hβ emission from several knots of low surface brightness, fast-moving ejecta. The presence of fast-moving hydrogen points toward a progenitor that had not entirely shed its hydrogen envelope prior to the supernova. The explosion that gave rise to 1E 0102 is therefore commensurate with a Type IIb supernova.

Key words: ISM: individual objects (SNR 1E0102.2–7219) – ISM: supernova remnants – nuclear reactions, nucleosynthesis, abundances – shock waves

1. Introduction

Core-collapse supernovae (CC SNe) mark the spectacular end of nuclear fusion processes within massive stars. Following the gravitational collapse of the stellar core and the subsequent explosion of the star as a supernova, freshly synthesized heavy elements are ejected at high velocity into the surrounding medium, thereby creating a supernova remnant (SNR). For the rare case of “oxygen-rich” (O-rich) supernova remnants (OSNRs), with typical ages ≤3000 years, the composition and spatial distribution of the stellar ejecta can be studied directly via the optical emission of its shock-heated atoms. These ejecta are detected at optical wavelengths primarily via the [O III] λλ4959,5007 lines (but see also Blair et al. 2000), following their encounter at a few 1000 km s^{-1} with the reverse shock (Sutherland & Dopita 1995). OSNRs thus offer extraordinary windows into the explosion mechanisms and medium, thereby creating a supernova remnant. For the handful of such OSNRs are known: the most prominent examples include Cassiopeia A, Puppis A, and G292.2+1.8 in our own Galaxy, a remnant in the galaxy NGC 4449 (Blair et al. 1984), N132D and 0540–69.3 in the Large Magellanic Cloud (LMC), and 1E 0102.2–7219 (hereafter 1E 0102) in the Small Magellanic Cloud (SMC). The latter was discovered in Einstein soft X-ray observations of the SMC by Seward & Mitchell (1981), who found it to be the second brightest X-ray source in the SMC. Dopita et al. (1981) classified 1E 0102 as an OSNR. Here, we report the discovery of optical emission from high-velocity supernova ejecta in 1E 0102 enriched in a number of elements not previously identified in 1E 0102, namely, hydrogen, sulfur, argon, and chlorine.

2. Detection of Sulfur-rich Ejecta

We observed 1E 0102 with the WiFeS Integral Field Spectrograph on the 2.3 m telescope of Siding Spring Observatory on 2016 August 7 and 8. In the reduced data cube we unambiguously detected faint, highly Doppler-shifted [S II] λλ6716,6731 emission (see Figure 1(a)), associated with the ejecta of this OSNR (see also Seitenzahl et al. 2017). Following this discovery, we performed follow-up observations of 1E 0102 using the Multi-Unit Spectroscopic Explorer (MUSE) in Service Mode at the Very Large Telescope on the night of 2016 October 7, as part of Director Discretionary Time (DDT) program 297.D-5058 (PI: F.P.A. Vogt) for 9 × 900 s exposures on-source. For details of the observations and the data reduction see Vogt et al. (2017a). In the [S II] images of 1E 0102 extracted from the MUSE data cube, the smaller pixel scale of the MUSE data compared to WiFeS (0′′/2 per spaxel versus 1′′/per spaxel) allows a much finer discernment of the spatial distribution of S-rich ejecta relative to the O-rich ejecta.
The MUSE imagery shows that the S II emission is patchy and asymmetric, aligning with localized segments of O III-emitting material along the eastern, western, and central regions. The sulfur-rich ejecta are detected at Doppler shifts ranging from −1776 km s$^{-1}$ to +958 km s$^{-1}$ (Figure 2(a)). In some of the brighter regions, S III $\lambda$9069, Ar III $\lambda$7136, and CI II $\lambda$8579 are also detected at consistent Doppler velocities (see Figure 3).
These data are the first detection in the optical of the long-sought-after (Lasker & Golimowski 1991; Blair et al. 2000) products of oxygen burning in the ejecta of the supernova that gave rise to 1E 0102. Fitted line fluxes (and some upper limits) of the brightest sulfur-rich knot (region 1 in Figure 1) are given in Table 1 for a selection of emission lines.

3. Discovery of the Fast-moving Hydrogen

Aside from the sulfur-rich emission, we also discovered several distinct high-velocity knots emitting in the Balmer lines of hydrogen (see Figures 1(f), 2(b), and 4). This Balmer emission is also observed from both blueshifted and redshifted material. The velocity shifts of the Hα and Hβ lines agree with the Doppler shifts of other prominent identified lines from the same extraction region, giving confidence in the line identification and that the knots are indeed high-velocity hydrogen-rich ejecta. The hydrogen-rich ejecta are detected at Doppler shifts ranging from $-1785 \text{ km s}^{-1}$ to $+786 \text{ km s}^{-1}$ (Figure 2(b)). Interestingly, the distribution of the Balmer-line emission somewhat correlates with the [S II] and to a lesser extent [O III] emission (see Figures 1(d), (e), (f) and 2(a), (b)). Comparison with the WiFeS data shows that emission from these lines also coincides with [Ne III] λ3889 near the center (see Figure 1(b)). Fitted line fluxes (and some upper limits) of the prominent Balmer-line emitting knot in the south (region 2 in Figure 1) are given in Table 1 for a selection of emission lines.

Figure 2. (a) Extent of the [S II] emission from Figure 1(e) in Doppler velocity. (b) Extent of the Hα emission from Figure 1(f) in Doppler velocity measured in the local frame of the SNR, relative to the narrow emission lines.

Figure 3. MUSE spectrum of region 1 (see Figure 1) exhibiting strong, blueshifted sulfur emission. The broad emission lines associated with the blueshifted ejecta by $v = 1655 \text{ km s}^{-1}$ (with respect to the narrow lines) are labeled in blue font, while the narrow emission lines at the Doppler velocity of the SNR are labeled in black font.
| Line       | $J^2_{\text{obs}}$ | $T^1_{\text{obs}}$ | $T^1_{\text{mod}}$ | $J^2_{\text{obs}}$ | $T^2_{\text{obs}}$ | $T^2_{\text{mod}}$ |
|------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| H$\beta$ 4861 | 9.0 ± 5.2          | 1.0                | 1.0                | 29.0 ± 2.5         | 1.0                | 1.0                |
| [O iii] 4959 | 5956 ± 18          | 662 ± 382          | 564                | 4264.7 ± 4.8       | 147 ± 13           | 147                |
| [O iii] 5007 | 18037 ± 25         | 2004 ± 1158        | 1632               | 12882.3 ± 7.5      | 444 ± 38           | 425                |
| [O ii] 5577  | 17.5 ± 9.6         | 1.94 ± 1.55        | 0.13               | 218 ± 1.3          | 0.75 ± 0.08        | 0.08               |
| He I 5876   | <2.7               | <0.7               | ...                | <4.5 <1.0          | <1.7 <0.1          | ...                |
| O I 6157    | <2.8               | <0.7               | 1.48               | 20.0 ± 1.9         | 0.69 ± 0.09        | 1.34               |
| [O i] 6300  | 638.8 ± 6.4        | 71 ± 41            | 22.5               | 951.6 ± 2.1        | 32.8 ± 2.8         | 7.58               |
| [O i] 6364  | 111.5 ± 9.2        | 12.8 ± 7.2         | 7.2                | 314 ± 2.7          | 10.8 ± 0.9         | 2.42               |
| Ne I 6507   | <7.3               | <1.9               | ...                | 30.4 ± 5.7         | 1.05 ± 0.22        | ...                |
| [N ii] 6548 | <1.3               | <0.34              | 0.01               | <3.6 <0.14         | 0.01               |                    |
| Hα 6563     | 35.4 ± 7.3         | 3.93 ± 2.4         | 4.1                | 140.1 ± 2.2        | 4.83 ± 0.42        | 4.06               |
| [N ii] 6583 | ...                | ...                | ...                | <1.9 <0.07         | 0.03               |                    |
| [S ii] 6717 | 353.4 ± 3.2        | 39.3 ± 23          | 39.2               | 15.7 ± 1.1         | 0.54 ± 0.06        | 0.45               |
| [S ii] 6731 | 558.0 ± 4.6        | 62.0 ± 35          | 31.5               | 12.9 ± 0.8         | 0.44 ± 0.05        | 0.32               |
| Ne I 6929   | <6.7               | <1.8               | ...                | 11.6 ± 4.2         | 0.40 ± 0.15        | ...                |
| [Ar iii] 7136 | 62.2 ± 6.2        | 6.9 ± 4.1          | 6.9                | <4.5 <0.17         | ...                | ...                |
| [Ca ii] 7291 | <7.7               | <2.0               | ...                | <9.0 <0.34         | ...                | ...                |
| [O iii] 7319 | 1123 ± 11          | 125 ± 72           | 89.6               | 9750 ± 1.9         | 33.6 ± 2.9         | 26.47              |
| [O ii] 7330 | 571 ± 25           | 63.4 ± 37          | 70.2               | 7350 ± 2.2         | 25.3 ± 2.2         | 21.35              |
| O I 7774    | 122.3 ± 6.2        | 13.6 ± 7.9         | 19.4               | 301.4 ± 1.5        | 10.4 ± 0.9         | 14.36              |
| O I 8446    | 17.6 ± 2.3         | 20.0 ± 12          | 11.9               | 98.2 ± 2.7         | 3.39 ± 0.31        | 2.71               |
| [Cl ii] 8579 | 22.4 ± 4.9         | 2.5 ± 1.5          | 2.48               | <7.7 <0.29         | ...                | ...                |
| [S ii] 9009 | 121.6 ± 4.6        | 13.5 ± 7.8         | 8.6                | <5.1 <0.19         | 0.13               |                    |
| O I 9263    | 43.4 ± 3.8         | 4.8 ± 2.8          | 9.0                | 169.5 ± 1.8        | 5.84 ± 0.51        | 2.65               |

Notes. Observed ($T^1_{\text{obs}}$) and shock model line intensities ($T^1_{\text{mod}}$) are also given relative to H$\beta$ = 1.0. The observed fluxes quoted have been corrected with the BRUTUS code (Vogt et al. 2017) for reddening with a Fitzpatrick (1999) reddening law with $R_V = 3.1$ and galactic extinction (Schlafly & Finkbeiner 2011) with $A_B$ = 0.134 and $A_V$ = 0.101 extracted from the NASA/IPAC extragalactic database (NED).

a We are quoting 1σ statistical errors of the Gaussian fit. Note that in cases of strong lines with very high signal to noise, such as, e.g., [O iii], systematic uncertainties dominate and the statistical errors underestimate the total uncertainty of the observed line flux.

b Not included in the MAPPINGS V shock model calculations, either because the upper limit does not lead to meaningful constraints or the line is not included in the code.

c A meaningful upper limit could not be determined in this case as the Doppler shift puts [N ii] 6583 on top of Hα.

### 4. Shock Model Calculations

We have constructed cloud shock models for regions 1 and 2 using the MAPPINGS V code with self-consistent pre-ionization as described by Sutherland & Dopita (2017). The structure of these O-rich shocks is quite different from those of normal plasmas (Itoh 1981; Dopita et al. 1984; Sutherland & Dopita 1995). First, in the post-shock region, the plasma cools very quickly, so that collisional ionization is never reached, and the plasma cools below 1000 K before significant recombination to un-ionized states has occurred. Second, the ionizing photon production in these shocks is high, so that they produce photoionized precursors. In these, the time dependence of the ionization is very important. Initially, the incoming plasma is exposed to hard photons left over from maintaining ionization in the precursor, and the fractional ionization is very low. As a consequence, the photo-heating much exceeds the cooling provided by the few electrons, and the plasma is strongly superheated. This is the region that dominates the emission of the low-ionization species. As the plasma becomes more fully ionized in its passage toward the shock front, the cooling dominates the photo-heating, and the plasma falls toward its equilibrium temperature of ≈100–200 K. In these shocks, the forbidden line emission from the leading edge of the photoionized precursor zone may be as important, or more important, than the forbidden line emission from the cooling region of the shock itself.

To model regions 1 and 2 we have used the iterative approach described by Sutherland & Dopita (2017) to model both regions. The observed ratios of [O i] to [O ii] to [O iii] constrain the shock velocities to be relatively low, 30–100 km s$^{-1}$, consistent with the model in which the O-rich knots arise in relatively dense ejecta passing through the reverse shock. The best-fit model requires a mixture of shock velocities to be present, as might be expected if there exist variations in the pre-shock density in the shocked cloud. For region 1, we mixed shock velocities between 50 and 90 km s$^{-1}$ to produce a satisfactory fit, while for region 2 the range of velocities required to produce a good fit was smaller, 40–50 km s$^{-1}$. For the region 1 best-fit model, the pre-shock density is $\approx 1.8 \times 10^{-21}$ g cm$^{-3}$, while for region 2, the pre-shock density is $\approx 5.4 \times 10^{-22}$ g cm$^{-3}$. Those correspond to ionic densities of 230 cm$^{-3}$ and 222 cm$^{-3}$, respectively.

In all of the models the magnetic parameter $\alpha$, the ratio of the magnetic pressure to the gas pressure in the precursor, was taken to be unity. We note that the assumption of magnetic pressure equal to the gas pressure in the shock precursor is one of energy equipartition, which will be strictly valid in a turbulent precursor medium. However, since the gas in the far precursor region is at very low temperature, a few tens of degrees K, this assumption is almost equivalent to the low magnetic field limit in the shock. The precursor magnetic field would have to be much higher to appreciably affect the results presented here, which seems to be unphysical. Therefore, our...
results are only weakly dependent on the exact value of the magnetic field.

Since the spectrum is dominated by emission from oxygen, we adjusted the abundances of the other observed elements relative to O. For region 1 we estimate the following abundances: \( \log \left( \frac{H}{O} \right) \sim -1.4 \), \( \log \left( \frac{N}{O} \right) \lesssim -4.5 \), \( \log \left( \frac{S}{O} \right) = -1.8 \), \( \log \left( \frac{Cl}{O} \right) = -3.5 \), and \( \log \left( \frac{Ar}{O} \right) = -2.3 \). While for region 2, we derive \( \log \left( \frac{H}{O} \right) = -1.0 \), \( \log \left( \frac{N}{O} \right) \lesssim -5.0 \), and \( \log \left( \frac{S}{O} \right) = -4.5 \). Typical errors on these figures are of the order of 0.2–0.3 dex.

5. Discussion and Conclusions

Chevalier (2005) argues that 1E 0102 is the remnant of a Type III/b supernova with a progenitor that lost most (but not all) of the H envelope before the explosion. The very low surface brightness of the Balmer emission makes a Type III progenitor implausible, but a Type IIb supernova type for 1E 0102 would place this remnant in the same category as the (in many regards similar) OSNRs Cas A and Puppis A. Indeed, fast hydrogen-rich knots, similar to those we report here, were discovered both in Cas A—known to stem from a Type IIb SN from light echo studies (Krause et al. 2008)—by Fesen et al. (1988) and Fesen & Becker (1991), and Puppis A (Winkler & Kirshner 1985), which Chevalier (2005) also assigned to a Type III/b SN progenitor. The high velocities of these features in Cas A (~6000 km s\(^{-1}\)) led Fesen et al. (1988) and Fesen & Becker (1991) to the conclusion that the hydrogen originated in the outermost photospheric region of Cas A’s progenitor, where the outflow velocities are highest. We note that the hydrogen-rich features in 1E 0102 exhibit somewhat lower Doppler shifts, up to about \(-1785 \text{ km s}^{-1}\).
nitrogen abundance of at least 10 times solar (Fesen et al. 1988, 2001). In stark contrast, in region 2 we find \([\text{NII}]\) \(\lambda 6583/\text{H}\alpha < 0.014\) (see Table 1), which is at least a factor of \(6/0.014 = 429\) lower than for the FMF in Cas A. This does not, however, imply a low nitrogen abundance relative to hydrogen. Our shock models indicate that very low shock speeds (40–50 km s\(^{-1}\)) are required to reproduce the observed spectrum in region 2. The approximately solar nitrogen to hydrogen ratio assumed for this calculation results in a line intensity of \([\text{NII}]\) \(\lambda 6583\) well below the observational upper limit and even a super-solar nitrogen to hydrogen ratio of twice the solar value, \(\sim 8 \times 10^{-5}\) (e.g., Lodders 2003), could be accommodated.

In addition to the new detections of fast-moving Balmer emission and S-rich material, we have also detected emission from argon ([Ar III] \(\lambda 1716\)) and chlorine ([Cl II] \(\lambda 8579\)). The abundances for our shock model that reproduces the spectrum for region 1 reasonably well (see Table 1 and Section 4) indicate a strong enhancement relative to H of O, S, Ar, and Cl. Using Russell & Dopita (1992), we find enrichments in region 1 of \(10^{3.77} \approx 235,000\) times the ISM abundance of the SMC for oxygen, \(10^{5.01} \approx 100,000\) times SMC for sulfur, \(10^{2.20} \approx 160,000\) times the ISM abundance of the SMC for chlorine, and \(10^{4.29} \approx 195,000\) times SMC for argon. The enhancement of products of oxygen burning (e.g., S, Cl, and Ar) indicates that nuclear fusion has partially proceeded past the previously known elements associated with explosive burning of the neon-carbon shell, i.e., C, Ne, O, and Mg. The enhancement in region 2 is less pronounced, with an overabundance of sulfur relative to hydrogen of \(\sim 200\) times the SMC value (Russell & Dopita 1992), and argon and chlorine are not detected.

The sulfur-rich ejecta appears more asymmetrically distributed than oxygen/neon and correlates with the hydrogen emission. The discovery of the fast hydrogen containing knots implies that the progenitor star retained part of its hydrogen envelope up moments before the supernova explosion. This makes a Wolf–Rayet progenitor of a Type Ib or Type Ic supernova unlikely for 1E0102. Based on the newly discovered fast-moving Balmer-line emission, we therefore favor a Type IIb supernova progenitor that was stripped of most—but not all—of its hydrogen envelope, possibly via interaction with a close companion star.

This research has made use of the following PYTHON packages: STATSMODEL (Seabold & Perktold 2010), MATPLOTLIB (Hunter 2007), ASTROPY, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013), APLPY, an open-source plotting package for PYTHON hosted at http://aplpy.github.com, MPFIT (Markwardt 2009; Moré 1978), and MAYAVI (Ramachandran & Varoquaux 2011). This research has also made use of MONTAGE, developed by the National Science Foundation under grant number ACI-1440620 and previously funded by the National Aeronautics and Space Administration’s Earth Science Technology Office, Computation Technologies Project, under Cooperative Agreement Number NCC5-626 between NASA and the California Institute of Technology, of the ALADIN interactive sky atlas (Bonnarel et al. 2000), of SAOImage DS9 (Joye & Mandel 2003) developed by Smithsonian Astrophysical Observatory, and of NASA’s Astrophysics Data System. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 297.D-5058 [A]. I.R.S. acknowledges support from the Australian Research Council Grant FT160100028. A.J.R. acknowledges support from the Australian Research Council through project numbers CE110001020 (CAASTRO) and FT170100243.

**References**

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33

Blair, W. P., Morse, J. A., Raymond, J. C., et al. 2000, ApJ, 537, 667

Blair, W. P., Raymond, J. C., Gull, T. R., et al. 1984, ApJ, 279, 708

Bonnarel, F., Femenique, P., Biémont, O., et al. 2000, A&AS, 143, 33

Chevalier, R. A. 2005, ApJ, 619, 839

Dopita, M. A., Binette, L., & Tuohy, I. R. 1984, ApJL, 329, L89

Dopita, M. A., Tuohy, I. R., & Mathewson, D. S. 1981, ApJL, 248, L105

Fesen, R. A., & Becker, R. H. 1991, ApJ, 371, 621

Fesen, R. A., Becker, R. H., & Goodrich, R. W. 1988, ApJL, 329, L89

Fesen, R. A., Morse, J. A., Chevalier, R. A., et al. 2001, ApJ, 122, 2644

Fitzpatrick, E. L. 1999, PASP, 111, 63

Hunter, J. D. 2007, CSE, 9, 90

Itoh, H. 1981, PASJ, 33, 521

Joye, W. A., & Mendel, E. 2003, in ASP Conf. Ser. 295, Astronomical Data Analysis Software and Systems XII, ed. H. E. Payne, R. I. Jedickejewski, & R. N. Hook (San Francisco, CA: ASP), 489

Krause, O., Birkmann, S. M., Usuda, T., et al. 2008, Sci, 320, 1195

Lasker, B. M., & Golimowski, D. A. 1991, ApJ, 371, 568

Lodders, K. 2003, ApJ, 591, 1220

Markwardt, C. B. 2009, in ASP Conf. Ser. 411, Astronomical Data Analysis Software and Systems XVIII, ed. D. A. Bohliender, D. Durand, & P. Dowler (San Francisco, CA: ASP), 251

Moré, J. J. 1978, Numerical Analysis (Berlin: Springer), 105

Ramachandran, P., & Varoquaux, G. 2011, IEEE Comput. Sci. Eng., 13, 40

Russell, S. C., & Dopita, M. A. 1992, ApJ, 384, 508

Slaflay, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103

Seabold, S., & Perktold, J. 2010, in Proc. of the 9th Python in Science Conference, 57, http://conference.scipy.org/proceedings/scipy2010/pdfs/seabold.pdf

Seitenzahl, I. R., Vogt, F. P. A., Terry, J. P., et al. 2017, in IAU Symp. 331, Supernova 1987A:30 Years Later—Cosmic Rays and Nuclei from Supernovae and Their Aftermaths (Cambridge: Cambridge Univ. Press), 178

Seward, F. D., & Mitchell, M. 1981, ApJ, 243, 736

Sutherland, R. S., & Dopita, M. A. 1995, ApJ, 439, 365

Sutherland, R. S., & Dopita, M. A. 1995, ApJ, 439, 381

Sutherland, R. S., & Dopita, M. A. 2017, ApJL, 835, 229, 34

Vogt, F. & Dopita, M. A. 2010, ApJ, 721, 597

Vogt, F. & Dopita, M. A. 2011, ApSS, 331, 521

Vogt, F. P. A., Pérez, E., Dopita, M. A., Verdes-Montenegro, L., & Borthakur, S. 2017, A&A, 601, A61

Vogt, F. P. A., Seitenzahl, I. R., Dopita, M. A., & Ghavamian, P. 2017a, A&A, 602, L4

Vogt, F. P. A., Seitenzahl, I. R., Dopita, M. A., & Ruiter, A. J. 2017b, PASP, 129, 058012

Winkler, P. F., & Kirshner, R. P. 1985, ApJ, 299, 981

Winkler, P. F., Kirshner, R. P., Hughes, J. P., & Heathcote, S. R. 1989, Natur, 337, 48

Wongwathanarat, A., Janka, H.-T., Müller, E., Plumbe, E., & Wannajo, S. 2017, ApJ, 842, 13