A-MUSE-ing Views of the Central Environment of the Vela Jr. and 1E0102-7219 Supernova Remnants

multi unit spectroscopic explorer

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Integral Field Spectroscopy: MUSE

Integral field spectroscopy (IFS) is a powerful observational astronomy technique that **performs spectroscopy and imaging simultaneously across a two-dimensional area**, making it highly effective for studying complex structures such as supernova remnants (SNRs).

IFS generates a **3-dimensional data product, called a data cube**: an array containing spectra for each spatial element in the field of view (Fig 1). In this work, we used the **Multi Unit Spectroscopic Explorer – MUSE** [1], a powerful integral field spectroscopy instrument installed on the Very Large Telescope (VLT) in Cerro Paranal, Chile. MUSE operates in the optical wavelength range, with high spatial resolution and wide coverage from 4800 Å to 9300 Å.

Vela Jr. SNR Compact Object and Its Optical Nebula

CXOU J085201.4–461753 is the central compact object (CCO) at the heart of Vela Jr. [2,3,4], a Galactic remnant discovered ~25 years ago through hard X-ray observations [5]. CCOs, a class of about 15 (including candidates) [6] neutron stars found near the centres of young core-collapse SNRs, are **detected only in the X-ray band**. They exhibit thermal emission and based on the spin properties of three detected pulsars, they are believed to have relatively low spin down magnetic fields (~$10^{10\text{-}11}$ G), in comparison to the traditional pulsars and magnetars.

To date, **Vela Jr. CCO is the only known Galactic CCO with an optical nebular counterpart** [7,8,9,10]. Using MUSE, we observed the central 2' field of the Vela Jr. SNR (Fig 2) in Wide Field Mode with Adaptive Optics (WFM-AO) configuration (*Program ID 0104.D-0092(B); P.I.: F.P.A.Vogt*). The sub-arcsecond spatial resolution of MUSE enabled us to **spatially resolve, for the first time, the emission distribution of the long-debated optical nebula** (8" in diameter) and characterize its emission line spectrum as being dominated by [N II]λλ6548,6583 emission.

Several key findings made possible by MUSE data [11]:

- The morphology of the optical nebula in Hα, which was previously unobserved, has revived the **bow shock nebula interpretation**.
- The optical nebula displays two distinct morphologies:
  - an **arc-like shape** that resembles a bow-shock nebula (observed in Hα)
  - **smooth blob structures** ([N II] and [S II] – also in [Ar III], [Fe II], [S III] but not shown in this poster).

  Meanwhile, no nebulosity structure was detected in Hβ and [O III].
- It exhibits a **significant overabundance of [N II] emission, ~33 times the intensity of Hα** (Fig 3), which is consistent with a **Wolf-Rayet (WR) star progenitor** and supports the notion that the Vela Jr. SNR is associated with a very massive progenitor [2,12].

  Our preliminary test model using MAPPINGS V [13] has demonstrated the feasibility of a very massive star in its WR stage producing an optical nebula akin to the one observed in Vela Jr. CCO and supports the suggestion that **very massive progenitors not necessarily making black holes**.

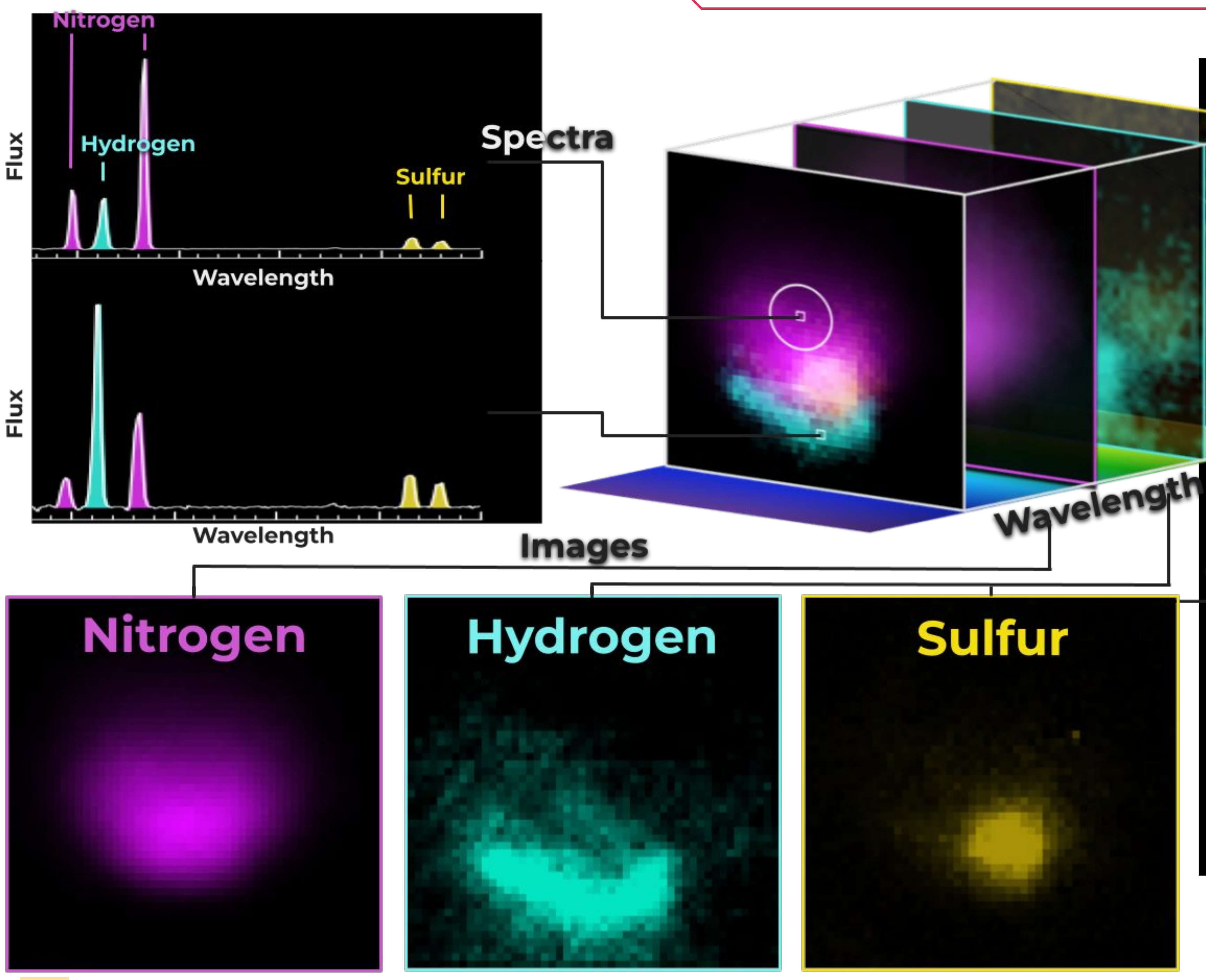

Fig 1. Illustration of a data cube using VLT's MUSE data of the central region of Vela Jr. CCO. *Credit Janette Suherli*

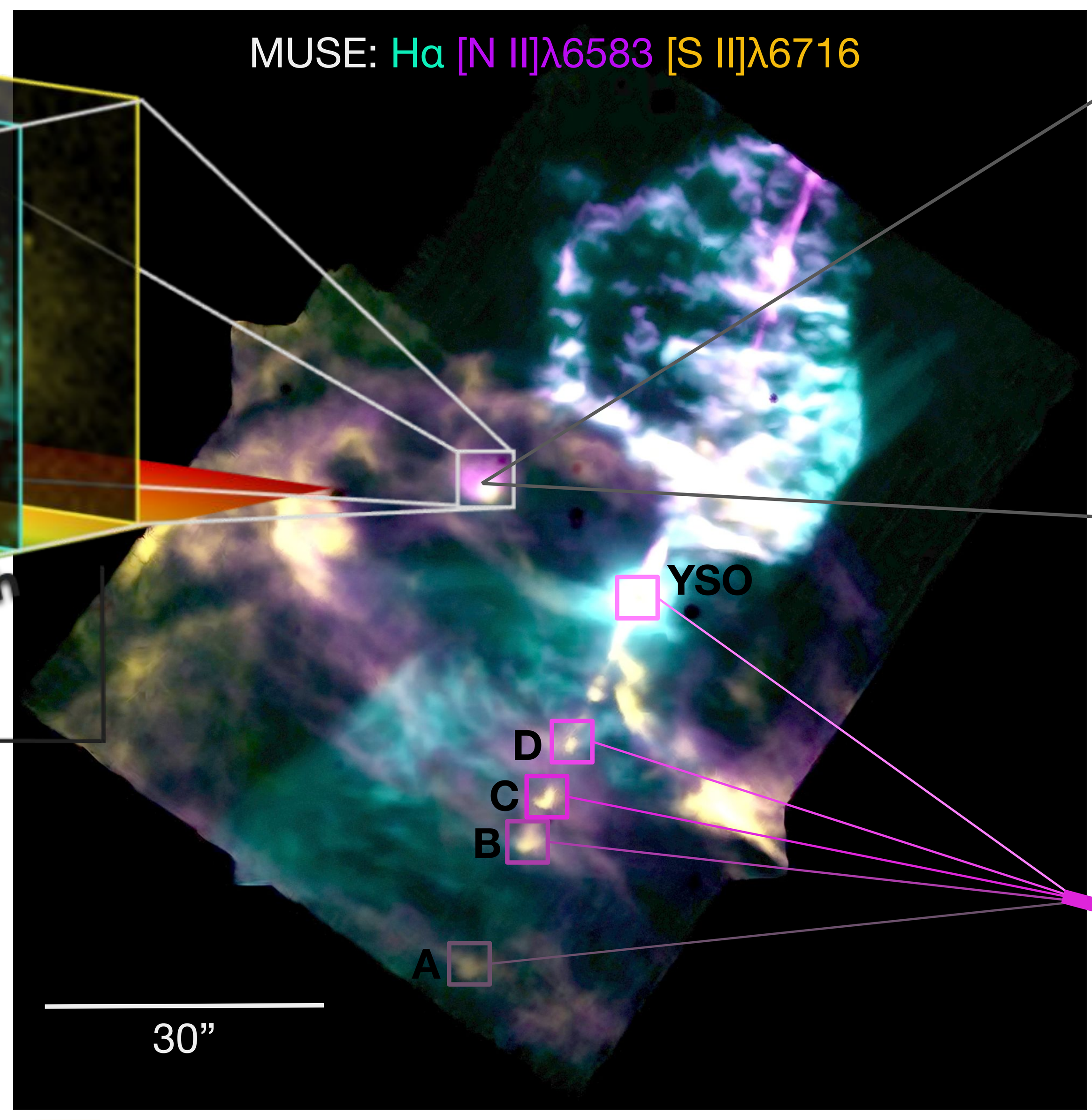

Fig 2. The continuum-subtracted MUSE image of the central 2' regions of Vela Jr. SNR [11], combining Hα (cyan), [N II] (magenta), and [S II] (yellow).

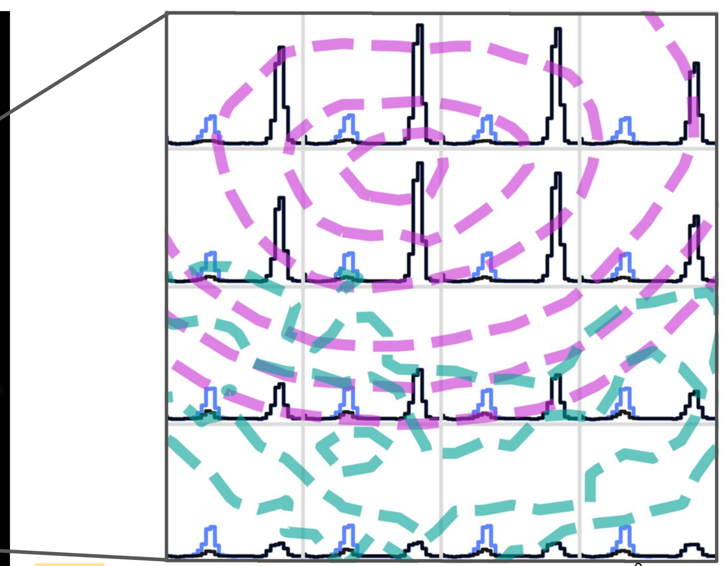

Fig 3. Hα and [N II] line profiles from 6555 Å to 6590 Å, integrated over 5 x 5 spatial pixels and overplotted on Hα (cyan) and [N II] (magenta) intensity contour.

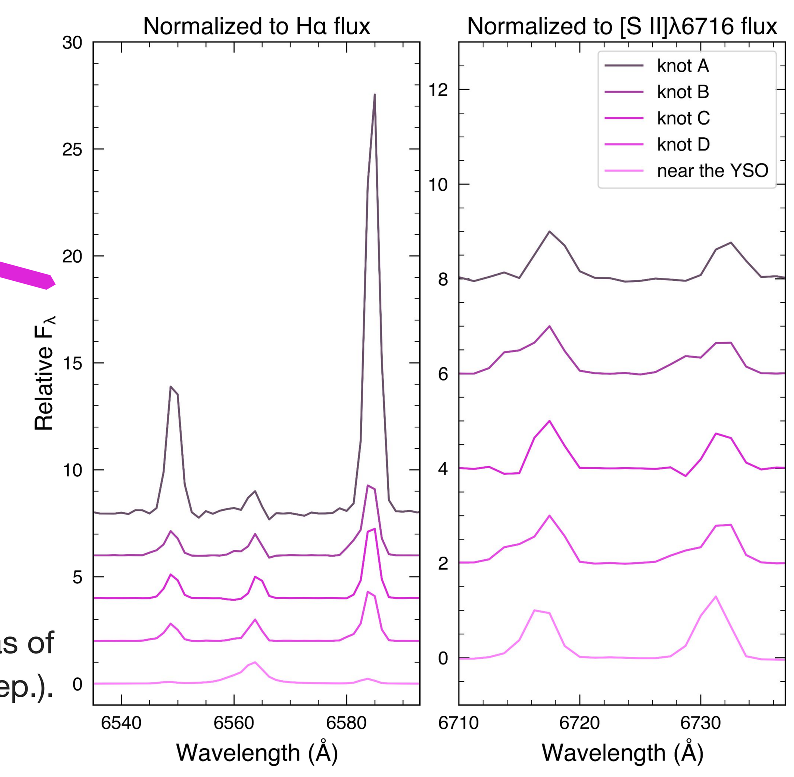

Fig 4. The normalized spectra of Hα and [N II], and [S II] lines for 5 areas of the YSO and along its southern HH jets (Suherli et al. in prep.).

Unusual Herbig-Haro Object Likely Associated with the CCO Nebula

To the west of Vela Jr. CCO optical nebula, we identified a striking Herbig-Haro (HH) object displaying prominent bipolar jets, showing signs of interactions with the optical nebula. These HH jets are associated with a young stellar object (**YSO**) **Wray 16-30**.

We extracted the integrated spectra of several knots along the HH jets from the MUSE cube (Fig 4), and subsequently corrected them for background emission. A single-component Gaussian function was fitted to the [N I], [NII], Hα, and [S II] emission lines of each knot. **Elevated [N II] / Hα ratio values** were observed for all knots, with knot A reaching a value of 30, notably **as high as the ratio observed in the Vela Jr. CCO optical nebula**. A compilation of available optical spectrophotometry data on HH objects by [14] indicates that the spectra of HH objects do not suggest nitrogen-rich compositions, with [N II]/Hα < 1.

The "Ring" in SNR 1E0102.2–7219

A serendipitous discovery of **an optical ring of Ne I and O I emission** in the Small Magellanic Cloud SNR 1E0102.2–7219 (E0102; Fig 5) was made in 2018 [15]. The optical ring surrounds an X-ray source that has been observed with Chandra, and it is argued to be a CCO candidate. The ring has a radius of ~2.1", and the **nature of the X-ray source as a CCO has been challenged** [16,17,18,19].

We observed the optical ring in E0102 with MUSE in Narrow Field Mode (NFM) configuration, with a total exposure time of 12 hours (*Program ID 0104.D-0092(A); P.I.: F.P.A.Vogt*).

- With MUSE NFM's Image Quality of ~0.1" (at 7500 Å), we observed a more detailed structure of the O I λ7774 emission, which is **diffuse with sharp edges on the inner side** (Fig 6).
- The faintness or lack of signal of Ne I λ6402 emission in the MUSE NFM data further suggests that the structure is not clumpy as previously assumed, but rather diffuse.
- The [O III]λλ4959,5007 emission is very bright and consists of both diffuse structures and fast-moving ejecta. We also observed a similar sharp inner edge in [O III] as seen in O I (Fig 5).

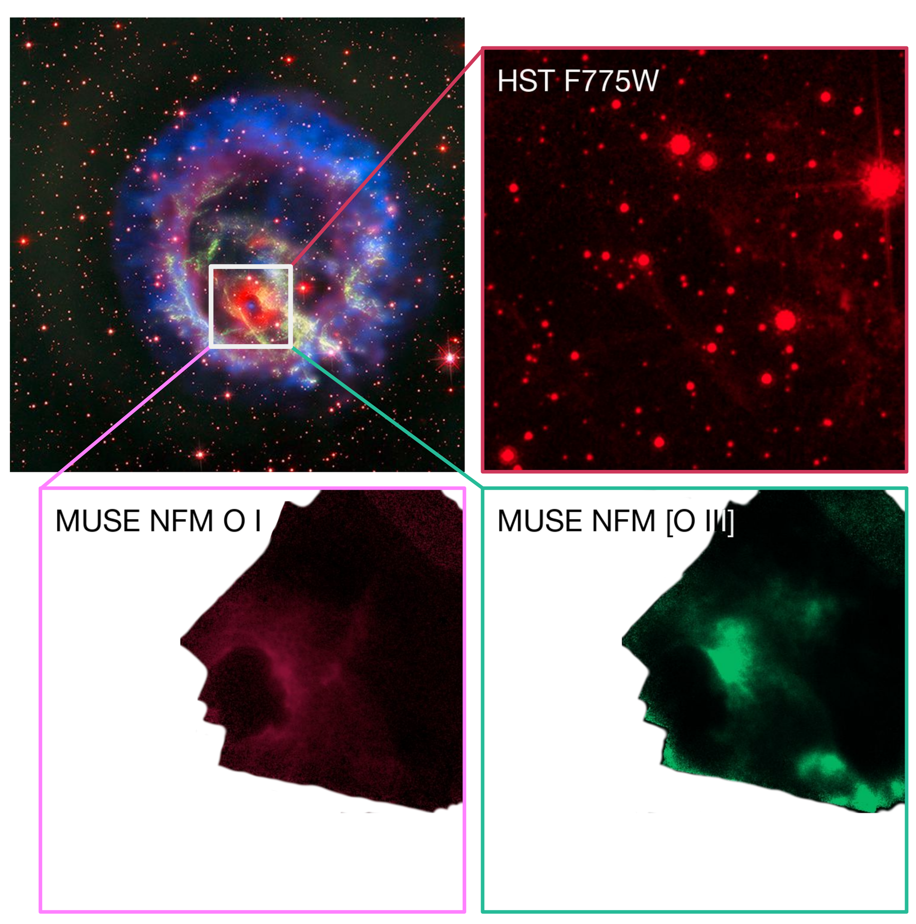

Fig 5. Top left: Composite of X-ray and optical images of E0102, the optical ring in red and X-ray source in blue at the centre of the ring (X-ray (NASA /CXC/ESO/F.Vogt et al); Optical (ESO/VLT/MUSE & NASA/STScI)); Top right: HST ACS/WFC F775W; Bottom left and right: MUSE NFM in O I and [O III].

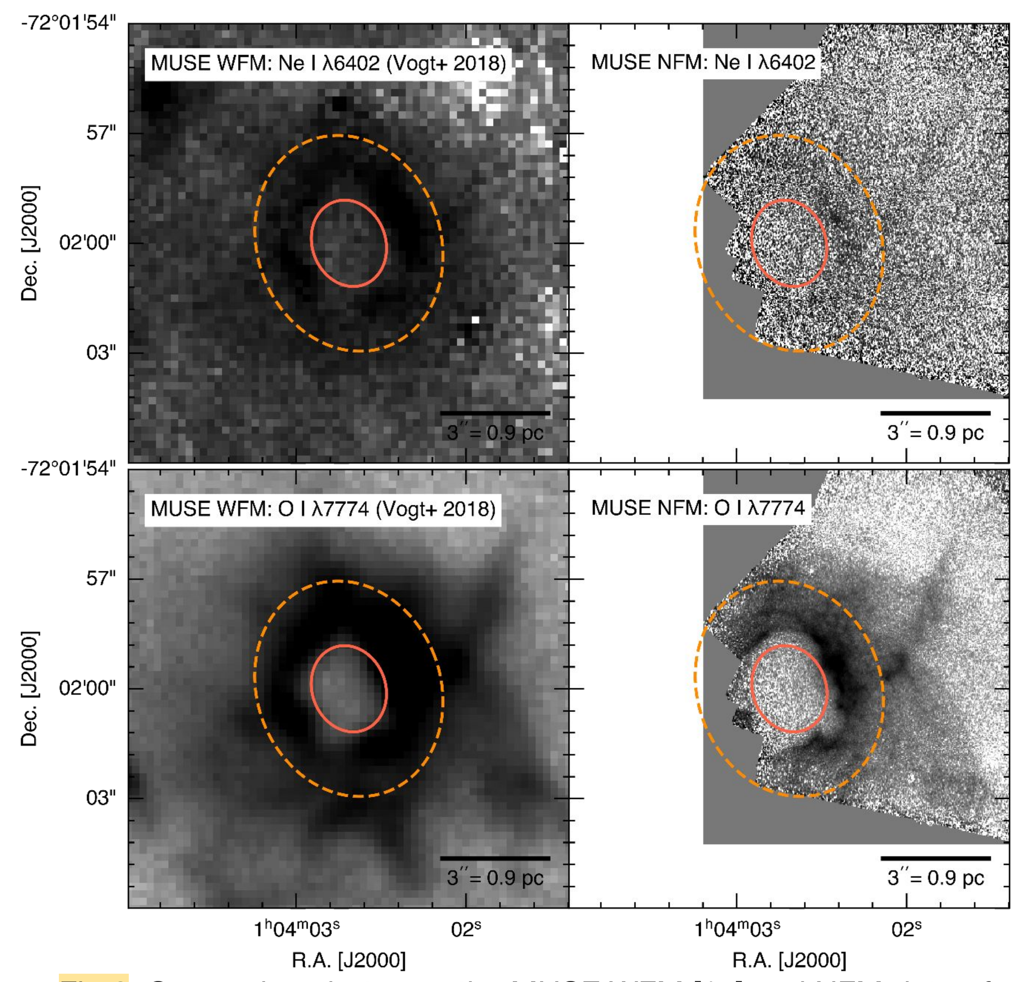

Fig 6. Comparison between the MUSE WFM [15] and NFM data of E0102 for Ne I (top row) and O I (bottom row) emission. The two ellipses trace the inner and outer edge of the optical ring and are centred at the X-ray source location (Suherli et al. in prep.).

[1] Bacon R., et al., 2010, in McLean I. S., et al, eds, SPIE Conf. Series Vol. 7735; [2] Slane P., et al., 2001, ApJ, 548, 814; [3] Mereghetti S., 2001, ApJ, 548, L213; [4] Pavlov G. G., et al., 2001, ApJ, 559, L131; [5] Aschenbach B., 1998, Nature, 396, 141; [6] Ferrand G. & Safi-Harb S., 2012, Advances in Space Research, 49, 1313; [7] Pellizzoni A., Mereghetti S., De Luca A., 2002, A&A, 393, L65; [8] Mignani R. P., et al., 2007, A&A, 473, 883; [9] Mignani R. P., de Luca A., Pellizzoni A., 2009, A&A, 508, 779; [10] Mignani R. P., et al., 2019, MNRAS, 486, 5716; [11] Suherli, J., et al., 2024, MNRAS, 527, 9263; [12] Allen G. E., et al., 2015, ApJ, 798, 82; [13] Sutherland R., et al., 2018, MAPPINGS V, record ascl:1807.005; [14] Raga, A. C., Böhm, K. H., Cantó, J., 1996, RMxAA, 32, 161; [15] Vogt F. P. A., et al., 2018, Nature Astronomy, 2, 465; [16] Hebbar P. R., et al., 2020, MNRAS, 491, 1585; [17] Long X., Gaetz T. J., Plucinsky P. P., 2020, ApJ, 904, 70; [18] Banovetz J., et al., 2021, ApJ, 912, 33; [19] Li C.-J., et al.,2021, ApJ, 915, 20

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