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Imaging the Radio Recombination Lines from M15's Planetary Nebula K648

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ABSTRACT

The globular star cluster M15 hosts the planetary nebula commonly called K648. Guided by available radio continuum data, we show how the next-generation Very Large Array (ngVLA) could be used to image dozens of Hydrogen recombination lines from this Galactic halo object. The lines could offer extinction-free probes of K648's dynamics at resolutions of about 200 mas (0.01 pc) and 10 km s^{-1}. The lines could also test expansion parallax models for a planetary nebula at a known distance.

Keywords: Planetary nebulae (1249)

1. MOTIVATION

The globular star cluster M15, at a distance of 10.0±0.5 kpc (McNamara et al. 2004), hosts the planetary nebula (PN) commonly referred to as K648 (Jacoby et al. 2017; Bond et al. 2020). K648 thus presents a rare opportunity to study a PN both in the Galactic halo and at a known distance. On scales less than 3.0″ (0.15 pc), HST imaging filtered for Hα, [O III] and [N II] emission lines reveals an outer shell, an inner shell and a striking northern arc of fast, low-ionization emission regions (FLIERs; Alves et al. 2000; Otsuka et al. 2015). Figure 1 illustrates these structures. HST studies of any southern FLIERs would be hindered by the presence of two red-giant-branch stars. Ground-based spectroscopy reveals emission line widths of about 10−20 km s^{-1}, but its spatial resolution is insufficient to probe the nebular dynamics (e.g., Otsuka et al. 2015). Studying K648's nebular dynamics with an HST-like spatial resolution could test FLIER models (e.g., Balick et al. 2020), plus expansion parallax models (e.g., Schoenberner et al. 2018) for a PN at a known distance.

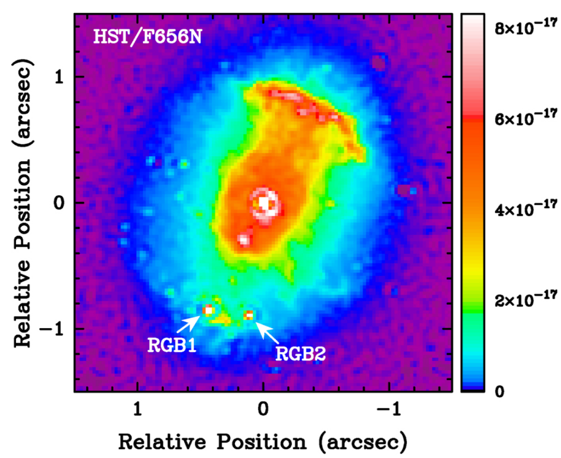

Figure 1. HST image of K648 filtered for Hα (Otsuka et al. 2015). Each axis spans 3.0″ (0.15 pc).

2. RRL ACCESS

Radio recombination lines (RRLs) occur throughout the radio spectrum, in sets of Hydrogen, Helium and Carbon lines reflecting cosmic abundances. Early imaging studies of PNe were limited by bandwidth to single Hydrogen lines and by sensitivity to nearby PNe (e.g., Roelfsema & Goss 1991; Rodriguez et al. 2010).

For ngVLA imaging, RRLs are so closely spaced in frequency that multiple sets of Hydrogen, Helium and Carbon lines could be simultaneously accessed with any receiver (Selina et al. 2022). Here, we choose Band 2 based on our desire for an HST-like spatial resolution. Figure 2 shows that Band 2 encompasses 42 Hydrogen α lines, from H122α to H81α, plus the associated Helium

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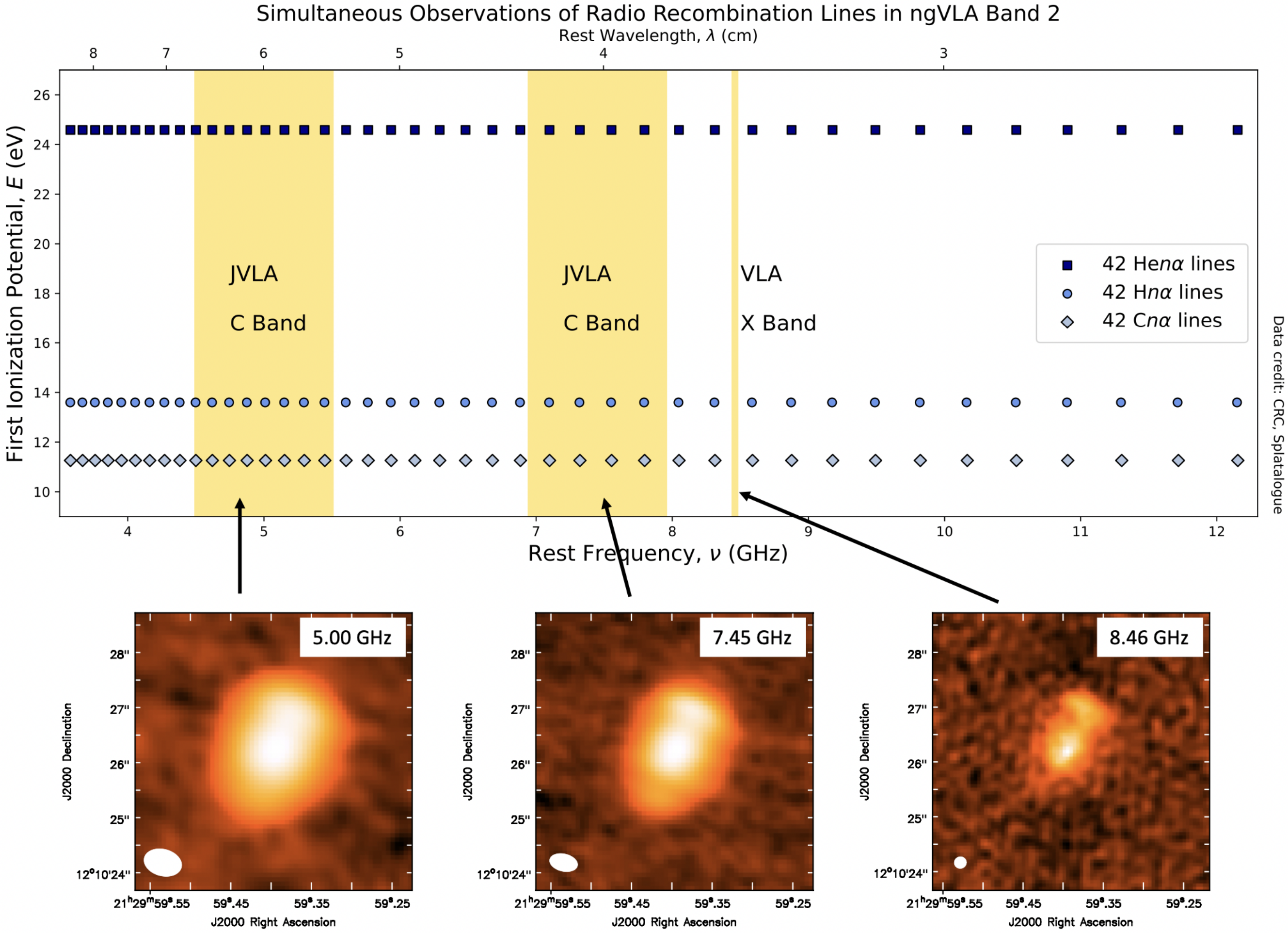

Figure 2. Top: Simultaneously accessible $n\alpha$ RRLs in ngVLA Band 2 for three abundant elements. ngVLA Band 2 spans 3.5−12.3 GHz. Bottom: Continuum images of K648. Filled ellipses show the synthesized beam dimensions at FWHM. Scale is $1.0'' = 0.05$ pc. Left to right, image peaks are 900, 550 and 200 μJy beam^{-1}, and rms noise levels are 4, 4 and 10 μJy beam^{-1}. Arrows point to the legacy observing bands.

and Carbon RRLs with ionization potentials higher and lower than Hydrogen.

3. RRL PREDICTIONS

K648's integrated flux densities from 1−10 GHz trace optically-thin, free-free emission (Knapp et al. 1996). Its electron temperature is estimated to be about 10,000 K (Otsuka et al. 2015). In LTE the related line-to-continuum ratio for H$n\alpha$ is about 10% and increases slowly with frequency (Kastner et al. 2018). Thus radio continuum images of K648 can be used to predict its H$n\alpha$ strengths.

Figure 2 shows continuum images of K648 from NSF's Karl G. Jansky Very Large Array (JVLA; Perley et al. 2011), used in Strader et al. (2012) and Tetarenko et al. (2016) but not the topic of those M15 studies. The flux density scale invoked, 2010, differs negligibly from that of Perley & Butler (2017). The JVLA images spatially resolve K648 and robustly confirm the faint northern feature reported by Gathier et al. (1983) in an image acquired with NSF's Very Large Array (VLA; Thompson et al. 1980). That radio feature seems to be related to the northern FLIER emission reported in the HST studies (Alves et al. 2000; Otsuka et al. 2015).

Figure 2 also shows a VLA continuum image of K648 with a spatial resolution of 220 mas (0.01 pc). The VLA image was made by Crossley et al. (2008) from data acquired for Bash et al. (2008), although K648 was not the topic of the latter study of M15. The flux density scale invoked, 1999.2, was adjusted to that of Perley & Butler (2017). The continuum peak suggests an H91α peak of about 20 μJy beam^{-1} for a 10 km s^{-1} line. Delineation of the northern radio feature is crisper and there are hints of a southern counterpart.

The ngVLA sensitivity calculator[1] for Configuration Revision D reports that a 65-hour observation of H91α near 8 GHz with the Main Array could achieve a spatial resolution of 200 mas (0.01 pc) and an rms noise of $4\,\mu$Jy beam^{-1} in a 10 km s^{-1} channel.

The peak signal-to-noise ratio of about 5 for H91α could be improved by stacking many RRLs, even after excising some lines damaged by radio frequency interference. Also, we could opt to do even better than the 10 km s^{-1} channels we have invoked, and use RRL stacking to offset the sensitivity reduction. For an example of RRL stacking in a JVLA band for a nearby PN, see Balser et al. (2022).

Formally, only the inner portions of the Mid Subarray are needed to reach the desired spatial resolution at Band 2's center of 8 GHz, but such a granularity is not available in the sensitivity calculator. In any case, retaining all Mid portions would help reach the desired spatial resolution at Band 2's lower edge.

4. RRL IMPLICATIONS

4.1. *Hydrogen RRLs in K648*

Hydrogen RRLs could be extinction-free tracers of the nebular dynamics throughout K648's outer and inner shells, as well as its FLIER region to the north and, possibly, the south.

A recent FLIER model posits that they are the remnants of magnetically-formed, fast-moving knots whose surfaces are becoming ionized by stellar UV or coronal heating (Balick et al. 2020). Forming such knots requires central star binarity, with obvious implications for the evolutionary paths of the progenitors of white dwarf stars.

Studying K648's nebular dynamics with an HST-like spatial resolution could also test expansion parallax models (e.g., Schoenberner et al. 2018) for a PN at a known distance.

Hydrogen RRLs are much less temperature sensitive than the optical forbidden lines (Kastner et al. 2018). Still, their line-to-continuum ratios could be an extinction-free way of measuring the electron temperature, thereby probing temperature fluctuations within the nebula.

JWST could spatially resolve K648 with its integral field units, but it only offers spectral resolving powers of 3500 or less[2]. For comparison, at the 8-GHz center of ngVLA Band 2 a 10 km s^{-1} channel spans 262 kHz and the spectral resolving power is about 31,000 (Selina et al. 2022).

4.2. *Helium and Carbon RRLs in K648*

Deeper RRL observations of K648 would be needed to probe the abundances of Helium and Carbon in this Galactic halo object. The Helium RRLs have a higher ionization potential (Figure 2), and could be extinction-free tracers of the nebular dynamics close to the central star(s). The Carbon RRLs have a lower ionization potential (Figure 2), and could be extinction-free probes of the ambient photodissociation region (Balser et al. 2016) with tie-ins to emerging molecular studies of PNe (e.g., Bublitz et al. 2019).

4.3. *RRLs in the Galactic Halo*

To our knowledge, no RRLs have been studied in objects in the Galactic halo. A further 12 PNe are generally held to be halo objects (Kwitter & Henry 2022), with each being in the ngVLA sky. ngVLA imaging of the RRLs from K648 could open a path for similar studies of a dozen more halo PNe.

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Facilities: HST, VLA, JVLA, ngVLA

Software: CASA (The CASA Team et al. 2022), matplotlib (Hunter 2007)

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