A Highly Variable Radio-Loud Quasar in the Epoch of Reionization

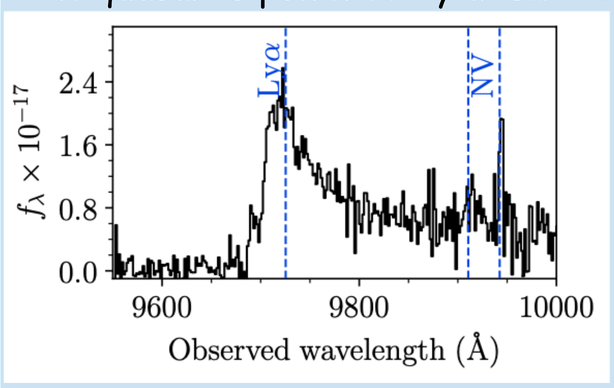
Emmanuel Momjian (NRAO)
E. Banados (MPIA), T. Connor (SAO), Y. Khusanova (MPIA),
R. Decarli (INAF), C. Mazzucchelli (UDP), C. Carilli (NRAO)

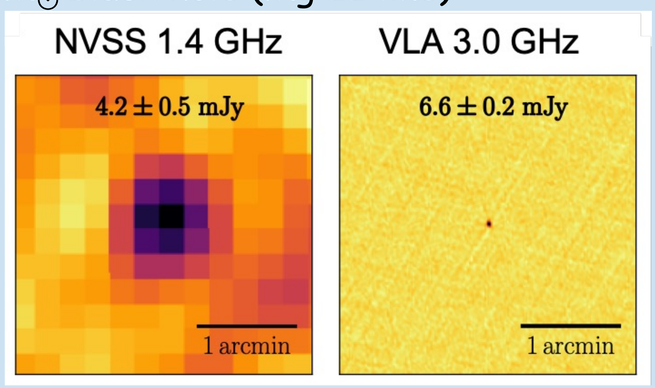
Abstract

Powerful radio jets are thought to play a key role in the formation and growth of supermassive black holes (SMBHs). They are also thought to have a significant effect on galaxy evolution. However, currently there is a dearth of radio sources at $z \geq 7$. Here, we present the discovery of the most distant radio-loud quasar known-to-date at $z = 7.0$, as well as the multi-wavelength follow-up studies of this unique object from radio to X-ray. We also discuss the nature of this highly variable source via multi-epoch multi-frequency radio observations, and present multi-frequency milliarcsecond (mas) resolution imaging and analysis of the radio emission from this source obtained with the Very Long Baseline Array (VLBA).

The Discovery

- The quasar was selected from the crossmatch of the optical DESI Legacy Imaging Surveys (DELS) and the 1.4 GHz NRAO VLA Sky Survey (NVSS; ~1').
- The source was found to unambiguously coincide with an unresolved radio source in the 3 GHz VLA Sky Survey images (VLASS; 2.5").
- We confirmed the nature of this source in 2020 with a FORS2 spectrum at the Very Large Telescope, revealing a quasar with a prominent Lyα emission line at $z = 7.0$.
- The quasar is powered by a 6.9×10^8 $M_\odot$ black hole (Mg II line)

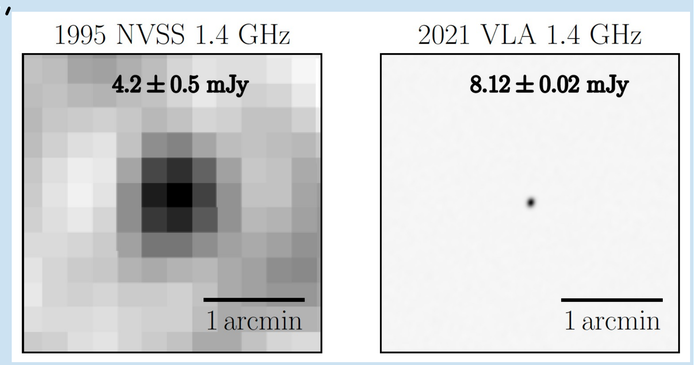


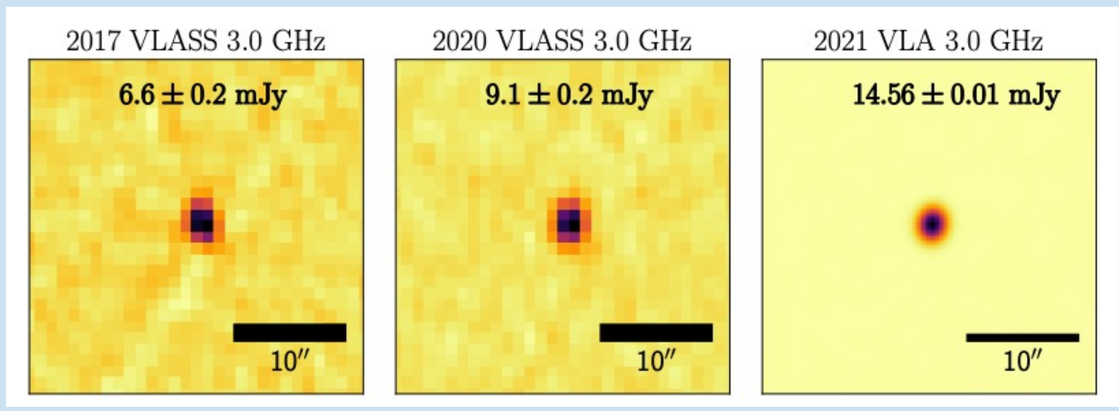


Left: Our discovery spectrum. Right: The NVSS 1.4 GHz and VLASS 3 GHz images used to select the quasar. The 3 GHz image shows that the quasar is the only strong radio source in this region of the sky.

Radio Variability

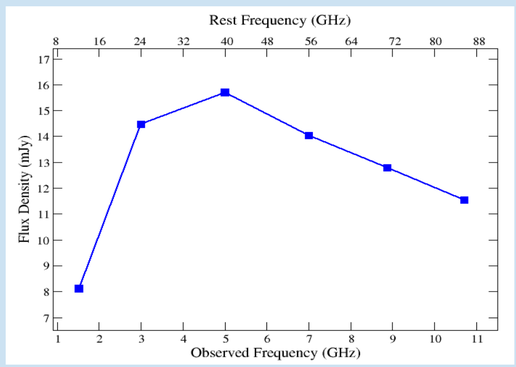
- The 1.4 GHz flux density of the quasar increased by more than 90% between 1995 and 2021, and at 3 GHz by more than 120% between 2017 and 2021.
- This source might not only be the most distant radio source known, but also the most distant blazar.





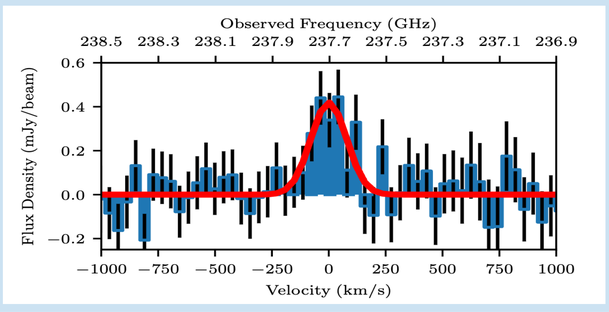
Radio SED

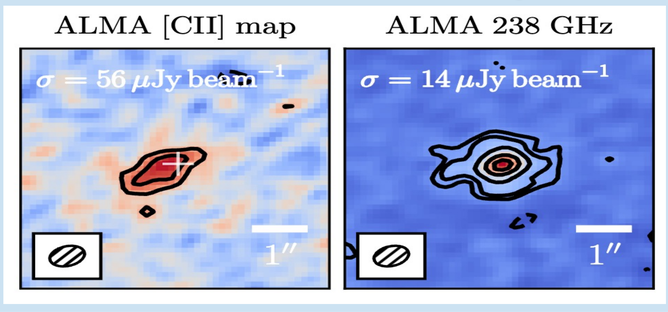
- VLA multi-band observations in 2021 show the SED peaking near 5 GHz, indicative of an extreme Gigahertz Peaked Spectrum (GPS) radio source.
- If the turnover is due to synchrotron self absorption, then the magnetic field strength is ~2 Gauss.



[CII] and mm Continuum

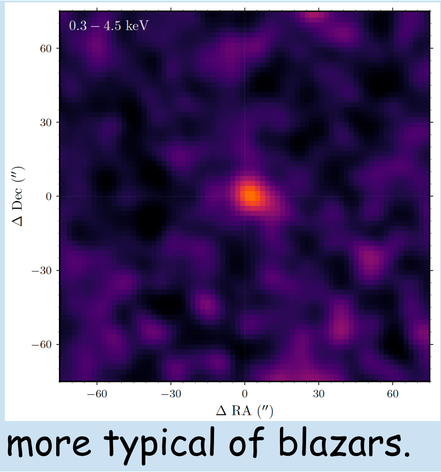
- Both [CII] line and 1.3 mm continuum emission are detected (shown below).
- The host galaxy of the quasar has a star formation rate of ~54 $M_\odot$/yr.





X-ray Detection

- XMM observed this source for ~ 50 ks.
- The broad band (0.3 - 4.5 keV) EPIC combined image is shown to the right.
- With an X-ray luminosity of ~3×10^{45} erg/s (rest frame 2-10 keV), it is one of the most luminous quasars seen in the early Universe.
- Its spectral slope (Gamma = 1.7 +/- 0.5) is softer than that of radio-quiet high-redshift quasars, but more typical of blazars.



Milliarcsecond Imaging

- The Very Long Baseline Array (VLBA) observations were carried out in late 2021 at 1.5, 4.5, and 7.3 GHz.
- The VLBA images at all the three observed frequencies reveal a single dominant source, supporting the blazar nature of this quasar (jet oriented toward us).
- The measured flux densities with the VLBA are lower at all the frequencies compared to the VLA measurements obtained a few months earlier - this may still be attributed to the high variability of the source.
- The deconvolved size of the source, as seen at the highest observed VLBA frequency (7.3 GHz), is 0.96 x 0.21 mas (~5 x 1 pc). The corresponding intrinsic brightness temperature is 9×10^9K.