THE HIGHEST REDSHIFT QUASAR AT \( z = 7.085 \): A RADIO-QUIET SOURCE

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ABSTRACT

We present 1–2 GHz Very Large Array A-configuration continuum observations on the highest redshift quasar known to date, the \( z = 7.085 \) quasar ULAS J112001.48+064124.3. The results show no radio continuum emission at the optical position of the quasar or its vicinity at a level of \( \geq 3\sigma \) or 23.1 \( \mu \)Jy beam\(^{-1}\). This \( 3\sigma \) limit corresponds to a rest-frame 1.4 GHz luminosity density limit of \( L_{\nu,1.4\,\text{GHz}} < 1.76 \times 10^{24} \text{ W Hz}^{-1} \) for a spectral index of \( \alpha = 0 \), and \( L_{\nu,1.4\,\text{GHz}} < 1.42 \times 10^{25} \text{ W Hz}^{-1} \) for a spectral index of \( \alpha = -1 \). The rest-frame 1.4 GHz luminosity limits are \( L_{\text{rad}} < 6.43 \times 10^6 L_\odot \) and \( L_{\text{rad}} < 5.20 \times 10^7 L_\odot \) for \( \alpha = 0 \) and \( \alpha = -1 \), respectively. The derived limits for the ratio of the rest-frame 1.4 GHz luminosity density to the B-band optical luminosity density are \( R_{L_{\nu},L_B} < 0.53 \) and <4.30 for the above noted spectral indices, respectively. Given our upper limits on the radio continuum emission and the radio-to-optical luminosity ratio, we conclude that this quasar is radio-quiet and located at the low end of the radio-quiet distribution of high-redshift (\( z \gtrsim 6 \)) quasars.

Key words: galaxies; active – galaxies; high-redshift – galaxies: individual (ULAS J112001.48+064124.3) – radio continuum: galaxies – techniques: interferometric

1. INTRODUCTION

The Sloan Digital Sky Survey (SDSS) revolutionized our understanding of the very high redshift universe through the identification of luminous quasars at \( z \geq 6 \) (Fan et al. 2000). In the subsequent decade, some 50 quasars have been discovered at \( z > 5.7 \). These high-redshift quasars are proving to be critical probes of the tail-end of cosmic reionization (Fan et al. 2006), through studies of the Gunn–Peterson effect in their rest-frame UV spectra. Observations in the centimeter and submillimeter have also shown that a substantial fraction of these sources (\( \sim 30\% \)) are extreme starburst galaxies, with star formation rates \( \sim 10^3 M_\odot \text{ yr}^{-1} \), and molecular gas masses \( \sim 10^{10} M_\odot \) (Wang et al. 2010; Carilli & Walter 2013). Hence, these systems are beacons to the coeval formation of supermassive black holes and their host galaxies within 1 Gyr of the big bang (Wang et al. 2010, 2013).

A curious characteristic of quasars is that their UV through X-ray spectra generally have properties indistinguishable across cosmic time (Fan et al. 2004; Shemmer et al. 2006; De Rosa et al. 2011). This puzzling result suggests that the most distant quasars establish their main emission characteristics quickly, even when the universe was only 7\% of its current age. One recent discovery that a change may occur at the highest redshifts is the detection of quasars with no emission from hot dust (\( \sim 1000 \text{ K} \)), likely associated with the accretion disk and always seen in lower redshift quasar spectra (Jiang et al. 2010). A second change in quasar characteristics is a possible decrease in the radio-loud fraction at the highest redshifts, which could indicate a change in the relative accretion modes and spin for the first quasars (Jiang et al. 2007; Wang et al. 2007; Dotti et al. 2013).

In this paper, we extend our deep radio imaging to the highest redshift quasar known, ULAS J112001.48+064124.3 (hereafter J1120+0641) at \( z = 7.085 \). This quasar was discovered in the United Kingdom Infrared Telescope Infrared Deep Sky Survey, and has an absolute magnitude of \( M_{1500} = -26.6 \pm 0.1 \) (Mortlock et al. 2011). The black hole powering the quasar has a mass of \( (2-3) \times 10^9 M_\odot \) (Mortlock et al. 2011; De Rosa et al. 2013), which is comparable to that of high-redshift quasars found in the SDSS. Observations with the Plateau de Bure Interferometer revealed a highly significant (\( > 9\sigma \)) detection of the [C\textsc{ii}] cooling line in the host galaxy of the quasar (Venemans et al. 2012). The underlying far-infrared (FIR) continuum was also detected, and depending on the assumed properties of the dusty spectral energy distribution (SED), it implies an FIR luminosity of \( L_{\text{FIR}} = 5.8 \times 10^{11} - 1.8 \times 10^{12} L_\odot \) and a total dust mass in the host galaxy of \( 6.7 \times 10^{5} - 5.7 \times 10^{6} M_\odot \).

We compare our results on the \( z = 7.085 \) quasar J1120+0641 to the well studied \( z \sim 6 \) quasar sample of Wang et al. (2007). Throughout this paper, we assume a concordance cosmology with \( \Omega_m = 0.27, \Omega_\Lambda = 0.73 \), and \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. OBSERVATIONS AND DATA REDUCTION

The observations of the \( z = 7.085 \) quasar J1120+0641 were carried out with the Karl G. Jansky Very Large Array (VLA) of the NRAO\(^3\) on 2011 August 9, 14, and 22, for a total of 4 hr. The array was in A-configuration (maximum baseline = 36.4 km). The observations spanned the frequency range 1–2 GHz. The WIDAR correlator was configured to deliver 16 adjacent subbands in dual polarization, each 64 MHz wide and 128 spectral channels.

The calibrator 3C 286 (J1331+3030) was used to set the absolute flux density scale and calibrate the bandpass response, and the compact source J1120+1420 was observed as the complex gain calibrator. Data editing, calibration, imaging, and analysis were performed using the Astronomical Image Processing System (AIPS; Greisen 2003) of the NRAO.

Each observing session was edited and calibrated separately. The data sets were then concatenated, imaged, and deconvolved. Imaging and deconvolution were performed through multifaceting (200 fields) to properly account for all the continuum sources in an area that covers 1.45 square degrees centered at the location of the \( z = 7.085 \) quasar J1120+0641.

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3. RESULTS

Figure 1 shows the 1–2 GHz continuum image centered at the optical position of the \( z = 7.085 \) quasar J1120+0641. The restoring beam size is 1′′29 × 1′′17 (position angle (P.A.) −57°). The contour levels are at −3, −2, 2, 3 times the rms noise level, which is 7.7 \( \mu \)Jy beam\(^{-1}\). The gray-scale range is indicated at the right side of the image in units of \( 10^{24} \text{ WH} \ z \). The plus sign indicates the optical position of the quasar, which is \( \alpha(2000.0) = 11^h20^m01^s48, \delta(2000.0) = +06°41′24″ \) (Mortlock et al. 2011).

Assuming a power-law \( (S \propto \nu^\alpha) \) radio SED, the 3σ limit on the radio continuum emission corresponds to a rest-frame 1.4 GHz luminosity density limit of \( L_{1.4 \text{GHz}} < 1.76 \times 10^{24} \text{ W Hz}^{-1} \) (or \( <1.76 \times 10^{31} \text{ erg s}^{-1} \text{ Hz}^{-1} \)) for a spectral index of \( \alpha = 0 \), and \( L_{1.4 \text{GHz}} < 1.42 \times 10^{25} \text{ W Hz}^{-1} \) (or \( <1.42 \times 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1} \)) for a spectral index of \( \alpha = -1 \). The resulting rest-frame 1.4 GHz luminosity limits for \( L_{\text{rad}} < 6.43 \times 10^8 L_\odot \) and \( L_{\text{rad}} < 5.20 \times 10^{10} L_\odot \) for \( \alpha = 0 \) and \( \alpha = -1 \), respectively.

4. DISCUSSION

In the following we compare the measured parameters of the \( z = 7.085 \) quasar J1120+0641 with the other high-redshift (\( z \sim 6 \)) quasars discussed by Wang et al. (2007).

The absolute magnitude of J1120+0641 is \( M_{1500} = -26.6 \pm 0.1 \) (Mortlock et al. 2011). Following Wang et al. (2007), and assuming a spectral index of −0.5, this results in a luminosity density at rest frame 4400 Å of \( L_{\nu,4400} = (3.3 \pm 0.3) \times 10^{24} \text{ W Hz}^{-1} \), and a B-band luminosity of \( L_B = \nu L_{\nu,4400} = (5.9 \pm 0.6) \times 10^{12} L_\odot \).

The radio-loudness or -quietness of a source can be investigated using the ratio of the observed radio to the optical flux densities, \( R \) (Schmidt 1970). For instance, a value of \( R \sim 10 \) separates the radio-loud and the radio-quiet sources for radio observations at 5 GHz and optical observations at 4400 Å (Kellermann et al. 1989). The \( K \)-corrected ratio of radio to optical power for given rest-frame radio frequency of \( v \), \( R^*_\nu \), provides a more consistent estimate among quasars of different redshifts (Sramek & Weedman 1980; Stocke et al. 1992). For the \( z = 7.085 \) quasar, and using the 3σ = 23.1 \( \mu \)Jy beam\(^{-1}\) noise level, the derived limit for the ratio of the rest-frame 1.4 GHz luminosity density to the B-band optical luminosity density, \( R^*_{1.4} = L_{\nu,1.4 \text{GHz}}/L_{\nu,4400} \), is \( R^*_{1.4} < 0.53 \) for \( \alpha = 0 \) and \( R^*_{1.4} < 4.30 \) for \( \alpha = -1 \). The values of \( R^*_{1.4} \) that separate radio-loud and the radio-quiet sources are \( \sim 10 \) and \( \sim 40 \) for \( \alpha = 0 \) and \( \alpha = -1 \), respectively. Therefore, irrespective of the assumed spectral index, the source J1120+0641 at \( z = 7.085 \) is a radio-quiet quasar.

Hereafter, and for proper comparison with the results obtained on other high-redshift quasars (\( z \sim 6 \)), we adopt their radio spectral index of \( \alpha = -0.75 \), and use the 2σ noise level of our VLA observations, which is 15.4 \( \mu \)Jy beam\(^{-1}\). This spectral index is appropriate because the majority (\( \sim 85\% \)) of extragalactic radio sources exhibit steep radio spectral slopes (e.g., Kimball & Ivezić 2008 and references therein). Furthermore, such a value is appropriate to characterize the synchrotron emission at low frequencies from a normal galaxy, i.e., a galaxy with a radio energy source that is not a supermassive black hole (Condon 1992). Wang et al. (2007) have adopted this value to investigate the star formation properties of the host galaxies of \( z \sim 6 \) quasars. For the above noted assumptions, the rest-frame 1.4 GHz luminosity density limit of the \( z = 7.085 \) quasar J1120+0641 is \( L_{\nu,1.4 \text{GHz}} < 5.62 \times 10^{23} \text{ W Hz}^{-1} \), and the rest-frame 1.4 GHz luminosity limit is \( L_{\text{rad}} < 2.06 \times 10^7 L_\odot \).

To further investigate the radio-quietness of J1120+0641, we show the logarithm of its rest-frame 1.4 GHz luminosity (\( L_{\text{rad}} \)) versus the logarithm of its B-band luminosity (\( L_B \)) in Figure 2. In this figure we also show the \( z \sim 6 \) quasars studied by Wang et al. (2007). The corresponding upper limit for \( R^*_1 = L_{\nu,1.4 \text{GHz}}/L_{\nu,4400} \) is \( R^*_1 < 1.70 \). For \( \alpha = -0.75 \), a value of \( R^*_1 \sim 30 \) would separate the radio-loud and the

![Figure 2. Logarithm of the rest-frame 1.4 GHz luminosity vs. the logarithm of the B-band luminosity of z > 6 quasars. The filled and open squares are detections and upper limits, respectively, from Wang et al. (2007). The star sign marks the z = 7.085 quasar J1120+0641 using the 2σ rms noise limit of our VLA observations and assuming a spectral index of \( \alpha = -0.75 \) for consistency with the non-detection limits reported by Wang et al. (2007), and its \( L_B \) value of 5.9 × 10^{12} L_\odot. The horizontal bar reflects the error in \( L_B \) (see Section 4). The dashed lines represent rest-frame radio-to-optical ratios R₁ of 1, 30, and 100. The R₁ ∼ 30 denotes the separation of radio-loud and radio-quiet quasars for the assumed spectral index (Wang et al. 2007).]
radio-quiet sources (Wang et al. 2007). The \( R_{1.4}^* \) of the quasar J1120+0641 is similar to the majority of the \( z \sim 6 \) quasars shown in Figure 2. Overall, the sample of the high-redshift quasars shown in Figure 2 is consistent with the trend of deceasing radio-loud fraction with increasing redshift (Jiang et al. 2007).

The mass of the black hole powering this \( z = 7.085 \) quasar is \((2-3) \times 10^7 \, M_\odot \) (Mortlock et al. 2011; De Rosa et al. 2013). Dotti et al. (2013) studied the relationship between supermassive black holes in galactic nuclei and their spins. These authors concluded that black holes with masses \( M_{\text{BH}} \sim 10^7 \, M_\odot \) can have either low or high spins depending on the fueling conditions. If the fueling of the black hole is not completely isotropic, then powerful radio jets that are stable in their orientation would be produced. However, if the black hole has been fed by random and isotropically distributed gas clouds, it will have lower spins and lower radio power. Therefore, the radio-quietness of the \( z = 7.085 \) quasar is consistent with a very massive black hole with lower spin due to isotropic accretion.

In the following we discuss the radio–FIR relation: Figure 3 shows the logarithm of the rest-frame 1.4 GHz luminosity density \((L_{\nu,1.4\,\text{GHz}})\) versus the logarithm of the FIR luminosity \((L_{\text{FIR}})\) range of J1120+0641, which is \(5.8 \times 10^{11} - 1.8 \times 10^{12} \, L_\odot\) and indicated by the horizontal line, along with other quasars at \( z \sim 6 \) from Wang et al. (2007). Yun et al. (2001) quantified the ratio of the FIR and radio flux densities through the parameter, \( q \equiv \log \left( \frac{L_{\text{FIR}}}{3.75 \times 10^{12} \, \text{W m}^{-2}} \right) - \log \left( \frac{S_{\nu,1.4\,\text{GHz}}}{\mu \text{Jy beam}^{-1}} \right) \), and found \( q = 2.34 \) for typical star-forming galaxies in the IRAS 2 Jy sample. For reference, we also plot galaxies from the IRAS 2 Jy sample (Yun et al. 2001) with \( L_{\text{FIR}} \geq 10^{11.35} \, L_\odot \) in Figure 3. The lower limits for the \( q \) parameter of the \( z = 7.085 \) quasar using the 2\( \sigma \) noise level of 15.4 \( \mu \text{Jy beam}^{-1} \) and the range of its FIR luminosity are \( q > 1.02 - 1.51 \).

There are four quasars at \( z \sim 6 \) that have both radio and FIR detections (Wang et al. 2007 and references therein; see also Figure 3). If the \( q \) value of the \( z = 7.085 \) quasar J1120+0641 were to be comparable to the average \( q \) value of these four quasars (\( q = 1.72 \)), then the expected radio flux density at the frequency of our observations would have been \( \sim 3.1 - 9.5 \, \mu \text{Jy beam}^{-1} \) (0.4\( \sigma \)–1.2\( \sigma \) significance) for the range of its \( L_{\text{FIR}} \). If, however, the \( z = 7.085 \) quasar were to follow the radio–FIR correlation (\( q = 2.34 \); Yun et al. 2001), then the expected radio flux density would have been \( \sim 0.7 - 2.3 \, \mu \text{Jy beam}^{-1} \) (0.1\( \sigma \)–0.3\( \sigma \) significance). The upper limit for the radio flux density of the \( z = 7.085 \) quasar J1120+0641 from our observations is not adequate to probe the radio–FIR relationship in the context of star formation. Deeper radio continuum observations are needed to carry out this type of study, but would require about 100 hr of integration time to go significantly (factor of \( \sim 5 \)) deeper than the current limit.

5. CONCLUSIONS

We have presented 1–2 GHz VLA A-configuration continuum observations on the highest redshift quasar known to date, the \( z = 7.085 \) quasar J1120+0641. The results show no radio continuum emission at the optical position of the quasar or its vicinity at a level of \( \gtrsim 3\sigma \) or 23.1 \( \mu \text{Jy beam}^{-1} \). For a range of assumed spectral indices of 0 to \( -1 \), we derive rest-frame 1.4 GHz luminosity density limits of \( L_{\nu,1.4\,\text{GHz}} < 1.76 \times 10^{24} - 0.52 \times 10^{25} \, \text{W Hz}^{-1} \), and rest-frame 1.4 GHz luminosity limits of \( L_{\text{rad}} < 6.43 \times 10^{6} - 5.20 \times 10^{7} \, L_\odot \). For the above noted range of spectral indices, the limits for the ratio of the rest-frame 1.4 GHz luminosity density to the B-band optical luminosity density, \( R_{1.4}^* \), are \( \gtrsim 0.53 - 4.30 \). The derived values clearly show that this source is a radio-quiet quasar, and the comparison with other high-redshift (\( z \sim 6 \)) quasars places it at the low end of the radio-quiet distribution of such quasars. We also derive lower limits for the \( q \) parameter of the \( z = 7.085 \) quasar J1120+0641. However, the sensitivity limits of our observations are not adequate to probe the star formation in the host galaxy of this quasar and study the radio–FIR relationship.

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