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Radio continuum observations of possible B-type stars in the halo of M 31*

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Abstract. We present Very Large Array (VLA) 5 GHz continuum observations of six point sources towards the halo of M 31, which have featureless optical spectra and magnitudes ranging from V=21.5–22.2, in order to determine whether these objects are BL Lacs. No radio emission coincident with the optical positions is detected to a 5σ noise level of between 0.08 and 0.11 mJy. The resulting upper limits to the two-point radio-to-optical spectral indexes from 5 GHz to 2500 Å ($\alpha_{\rm RO}$) are less than 0.30 for all of the sample. These observations make it highly likely that these objects are not BL Lacs, and hence strengthens the case that they are normal B-type stars in the halo of M 31.

Key words: galaxies: BL Lacertae objects: general – galaxies: halos – galaxies: individual: M 31 – radio continuum: general – stars: early-type

1. Introduction

In the halo of the Milky Way, the vast majority of observed stars are of late-type and exist in Globular Clusters (Freeman 1987). However, there also exists a population of isolated blue stars at high Galactic latitudes. Multi-wavelength spectroscopic analysis of a number of these objects using model atmosphere codes (Keenan 1997 and references therein) suggests that they are normal OB-type stars at z-distances from the Galactic plane ranging from $\sim$ 2–25 kpc. Most have probably been ejected from the Galactic disc via dynamical interactions within stellar clusters or as a result of supernova explosions in close binaries (Blaauw 1993). However, there is a small group of objects whose short evolutionary lifetimes and large z-distances imply that they have formed in the halo itself. This is difficult to understand, as currently star formation is believed to occur in high density molecular clouds (Shu et al. 1987), and the interstellar gas density is very low (Sembach & Danks 1994). An alternative possibility is that these 'halo' stars are in fact nearby, subluminous objects such as the post-Asymptotic Giant Branch stars, whose spectra mimic those of normal stars (Tobin 1991; McCausland et al. 1992).

Establishing the true evolutionary status of high latitude early-type stars is also vital due to their importance as tracers of halo interstellar gas and high velocity clouds (Wakker & van Woerden 1997), both in the optical using ground-based telescopes (Keenan et al. 1995) and in the ultraviolet with the Hubble Space Telescope (Savage & Sembach 1996).

In view of the above, we have embarked upon a search for normal Population I OB-type stars in the halo of the near edge-on spiral galaxy M 31. At the distance modulus of M 31 ($\{m$–$M_0\}$=24.4; Freedman & Madore 1990), a main-sequence early B-type star would have an apparent magnitude of $\sim$ 22 (Jaschek & Jaschek 1987). In a previous paper (Hambly et al. 1995), UBV imaging observations were used to identify 9 stellar-like objects in the outer regions of M 31, with magnitudes and colours consistent with a B-type classification. These candidates were followed up with low-resolution spectroscopy on the 4.2-m William Herschel Telescope (Hambly et al. 1995). Of the 9 objects, one showed strong absorption in the Balmer series, and has a radial velocity consistent with it being a DA white dwarf within our Galaxy. The remaining 8 have flat, featureless spectra, and hence cannot be DA white dwarfs. Nor is it likely that they are QSOs, as these show broad emission features, even allowing for redshifting to the wavelength region of the Hambly et al. (1995) observations (Strittmatter & Williams 1976). The remaining non-stellar possibility is that they are BL Lacs, a rare type of active galactic nuclei (AGN) characterised by a lack of prominent emission lines and a core-dominated radio morphology that is highly variable (Angel & Stockman 1980; Kollgaard 1994). Currently there are $\sim$ 280 identified BL Lacs out of $\sim$ 8000 known AGN.

In order to discriminate between a BL Lac and a B-type star, possible avenues include determining the optical-to-X-ray spectral index, which is known to lie in a narrow range for BL Lacs (Laurent-Muehleisen et al. 1999), or looking at the K-band flux which would be higher for a BL Lac, with its power-

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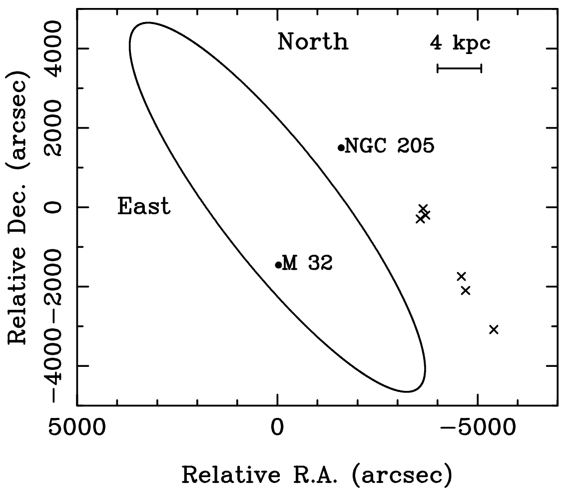

Fig. 1. Schematic diagram showing positions of the six objects imaged by the VLA in this paper and marked as crosses. The large ellipse represents the stellar disc of M 31 with a radius of 20 kpc. This has assumed coordinates taken from Crane et al. (1992) of RA=00$^{\mathrm{h}}$42$^{\mathrm{m}}$44.33$^{\mathrm{s}}$ Dec.=+41°16′08.6″ (J2000).

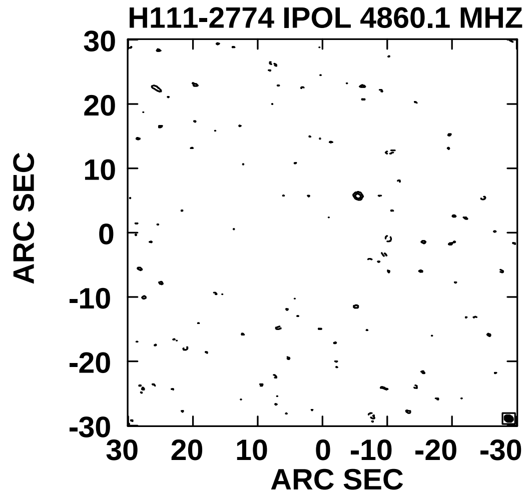

Fig. 2. VLA 5 GHz continuum image towards 111–2774 centred upon RA=00$^{\mathrm{h}}$37$^{\mathrm{m}}$16.4$^{\mathrm{s}}$, Dec=41°12′51.8″ (J2000). Contour levels (3σ) are at 0.06×(–1,1,2,3) mJy.

law spectral shape, than for a B-type star. However, at the faint magnitudes of the objects from Hambly et al. (1995), neither method is practicable. We did search the ROSAT public archive for an X-ray detection, but to no avail.

The remaining possibility is to measure the radio flux density. Unlike B-type stars, BL Lacs are known to be radio loud (e.g. Stocke et al. 1990), and hence the lack of any radio emission measured at the necessary sensitivity would rule out a BL Lac classification. Thus the current paper describes VLA 5 GHz radio observations towards the six brightest objects from the sample of Hambly et al. (1995). These have magnitudes ranging from V=21.5 to 22.2, and (B–V) colours from –0.12 to –0.05. The location of these objects with respect to the centre of M 31 is shown in Fig. 1. If the six objects were in the plane of the disc, they would lie at galactocentric radii between $\sim$ 37–41 kpc, outside both the stellar and H I radii of M 31 which are at distances of $\sim$ 20 kpc and 30 kpc, respectively (Brinks & Shane 1984). At such a radius from the centre, the gas density is too low to initiate star formation in the manner described by Kennicutt (1989). Alternatively, if the objects lie parallel to the major axis of M 31 they would have a z-distance of $\sim$ 6 kpc, again comfortably outside the stellar and H I discs.

Sect. 2 of this paper describes the radio observations and data reduction, Sect. 3 gives the results and Sect. 4 contains the conclusions.

2. VLA 5 GHz observations and data reduction

The VLA continuum observations presented in this paper were acquired during two observing sessions in 1999. Both used the standard continuum mode at a frequency of 5 GHz, using 27 antennae and with each of the two intermediate frequencies (IFs) having a bandwidth of 44 MHz. The first data were taken on October 25 using the ‘AB’ configuration of the VLA, during which a total integration time per object of between 45 and 60 minutes was obtained. This time was split up into 15 minute segments, with observations of different pointings being interleaved with each other in order to improve the UV coverage. The second session on November 1 used the ‘B’ configuration for a further 15 minutes for all positions except 108–871, for which an extra 60 minutes of observing time was obtained. For both sessions the phase calibrator 0038+416 was observed every 15 minutes, with 3C 48 (0137+331) acting as the amplitude calibrator being observed at the start and end of both runs.

Data were reduced using standard methods within AIPS[1]. This included flagging of bad data, and amplitude and phase calibration. The assumed flux density of 3C 48 was 5.48 Jy. Because 3C 48 is resolved by the longer baselines, only the inner 3 antennae from each arm were used in the calibration process. For the secondary calibrator (0038+416), the derived value for the flux density was 0.57 Jy. After calibration, the UV data were inverted using natural weighting and cleaned within IMAGR. The resulting maps have beamsizes of $\sim 2\times2$ arcsec^2 and rms noise values (σ) of $\sim$ 0.02 mJy. No primary beam correction was performed. As well as the maps from the individual sessions, a combined image from both sessions was obtained by addition in the map plane.

3. Results

Fig. 2 depicts the Stokes I-band 5 GHz radio map of the inner 1 arcmin^2 towards 111–2774. This is the only case where a radio detection exceeding 5σ was observed close to the stellar position. However, the detection is some 8 arcsec away from the optical position and so is unlikely to be associated.

Table 1 shows the results of the VLA observations. The V-band magnitudes and coordinates are taken from Hambly et

[1] AIPS is distributed by the National Radio Astronomy Observatory, USA

Table 1. Results of the VLA 5 GHz observations. Coordinates are of equinox 2000.

Object	RA hh mm ss	Dec ° ′ ″	V (mag.)	VLA 5GHz 5σ noise (mJy)	$\alpha_{\rm RO}$ ($S_{\rm 5GHz}$ to $S_{5500\,\rm Å}$)	$\alpha_{\rm RO}$ ($S_{\rm 5GHz}$ to $S_{2500\,\rm Å}$)
178–17	00 34 51.4	+40 24 46	21.7	0.10	<0.22	<0.27
155–184	00 35 51.2	+40 41 10	21.9	0.10	<0.24	<0.29
144–511	00 35 59.6	+40 47 06	21.8	0.11	<0.23	<0.28
111–2774	00 37 16.4	+41 12 52	21.5	0.11	<0.22	<0.27
108–871	00 37 21.7	+41 15 36	22.2	0.08	<0.24	<0.29
111–2383	00 37 28.1	+41 11 17	21.7	0.10	<0.22	<0.27

al. (1995), with the latter being transformed into equinox 2000 using COCO (Wallace 1995). Two values for the radio-to-optical spectral index ($\alpha_{\rm RO}$) are shown. This is defined as (Ledden & O'Dell 1985);

$$\alpha_{\rm RO} = -\frac{\log_{10}(S_{\rm radio}/S_{\rm optical})}{\log_{10}(\nu_{\rm radio}/\nu_{\rm optical})}, \quad (1)$$

where $S_{\rm radio}$ is a flux density corresponding to 5 times the RMS noise in the centre of our radio maps at a frequency ($\nu_{\rm radio}$) of 5 GHz, and $S_{\rm optical}$ is the optical flux density at a frequency ($\nu_{\rm optical}$) corresponding to a wavelength of either 2500 Å or 5500 Å. At 5500 Å this flux density was derived directly from the V-band magnitude, and at 2500 Å by assuming a spectral index of –1.0 (Laurent-Muehleisen et al. 1999). Of course, the optical flux derived from the magnitude is an overestimate of the optical non-thermal flux in an AGN, since the optical magnitude is given for the entire system (i.e. galaxy plus active nucleus). However, the total optical flux is what is used by most authors and is hence useful for comparison purposes. It is finally noted that as there were no positive radio detections towards the optical positions, the $\alpha_{\rm RO}$ values shown are upper limits.

4. Discussion and conclusions

The lack of radio emission from the current sample strongly suggests that they are not BL Lacs, which are radio-loud as a class of objects. In a sample of 23 X-ray selected BL Lacs, Sambruna et al. (1996) found only one object with a 5 GHz to 5500 Å spectral index of less than 0.25, the 5σ limiting value for our data. Additionally, all of the 29 radio-selected BL Lacs listed in Sambruna et al. (1996) have a 5 GHz to 5500 Å spectral index exceeding 0.35. Similarly, in a sample of 127 BL Lacs, Laurent-Muehleisen et al. (1999) found that only 12 per cent have a two-point radio to optical spectral index from 5 GHz to 2500 Å of less than 0.30, the 5σ limiting value from our data.

It is thus probable that the six objects in our sample are not any type of AGN. The remaining possibilities include B-type stars in the halo of M 31, or sub-luminous stars in the Milky Way. Even with the current generation of 8-m telescopes, obtaining optical spectroscopy at the necessary signal-to-noise to distinguish between these possibilities will prove challenging.

We finally note that identification of blue stars with such magnitudes around M 31 would provide definitive evidence for the formation of normal OB-type stars at large distances from the planes of spiral galaxies. Furthermore, it should be possible in the longer term to determine the z-distribution of such stars, which will allow a direct comparison with the theories suggested to explain their existence.

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