Giant Gas Halos in Radio Galaxies: A Unique Probe of the Early Universe

H. RÖTTGERING, G. MILEY and R. VAN OJIK, Leiden Observatory, The Netherlands

1. Introduction

Radio galaxies are important laboratories for studying the early Universe, because they generally emit three components (IR-optical-UV continuum, emission lines and radio continuum) that are all highly luminous. Unlike quasars, the various emission components of radio galaxies are spatially extended and well resolved from the ground. Not only can different diagnostics be derived for each of these components, but studies of the relationships between them can place unique constraints on the emission mechanisms, the contribution of stellar and non-stellar sources, the dynamical state of the thermal plasma, the physical state of the galaxian environment and the star-formation history. These properties are relevant to the formation and evolution of galaxies, active nuclei and radio sources.

During the last decade the number of known radio galaxies with measured redshifts well over 2 has grown dramatically. There are now more than 70 radio galaxies with $z > 2$. This redshift corresponds to look-back times of ~ 90%, close to the epoch at which the galaxies must have formed. It also corresponds to the peak of the "AGN era", when the space-density of luminous quasars and radio galaxies was several hundred times larger than the present value.

Several years ago it came as a big shock when it was discovered that, unlike the case for nearby radio galaxies, the radio emission of $z > 0.6$ radio galaxies is roughly aligned with the optical/IR continuum (Chambers, Miley and van Breugel, 1987; McCarthy et al., 1987). Several models have been proposed or considered to account for this alignment effect (e.g. see McCarthy, 1993). The two most promising models are scattering of light from a hidden quasar by electrons or dust (Tadhunter et al., 1989; Fabian, 1989) and star formation stimulated by the radio jet as it propagates outward from the nucleus (Chambers, Miley and van Breugel, 1987; McCarthy et al., 1987; De Young, 1989; Rees, 1989; Begelman and Cioffi, 1989). Other scenarios involve (i) inverse Compton scattering of CMB photons, (ii) enhancement of radio luminosity by interaction of the jet with an anisotropic parent galaxy, (iii) alignment of the angular momentum of the nuclear black hole with an anisotropic protogalactic distribution and (iv) nebular continuum emission associated with strong emission line regions. Although polarisation results suggest that dust scattering is occurring, as yet no single model for the radio/optical alignment is satisfactory (see Longair, Best and Röttgering, 1995).

Almost half the known high-redshift galaxies were found in the context of an ESO Key Programme in which we were involved. The results formed the basis of the Ph.D theses of Huub Röttgering and Rob van Ojik and have been presented in several articles. Two previous Messenger articles described our techniques for finding high-redshift objects and the preliminary results of the Key

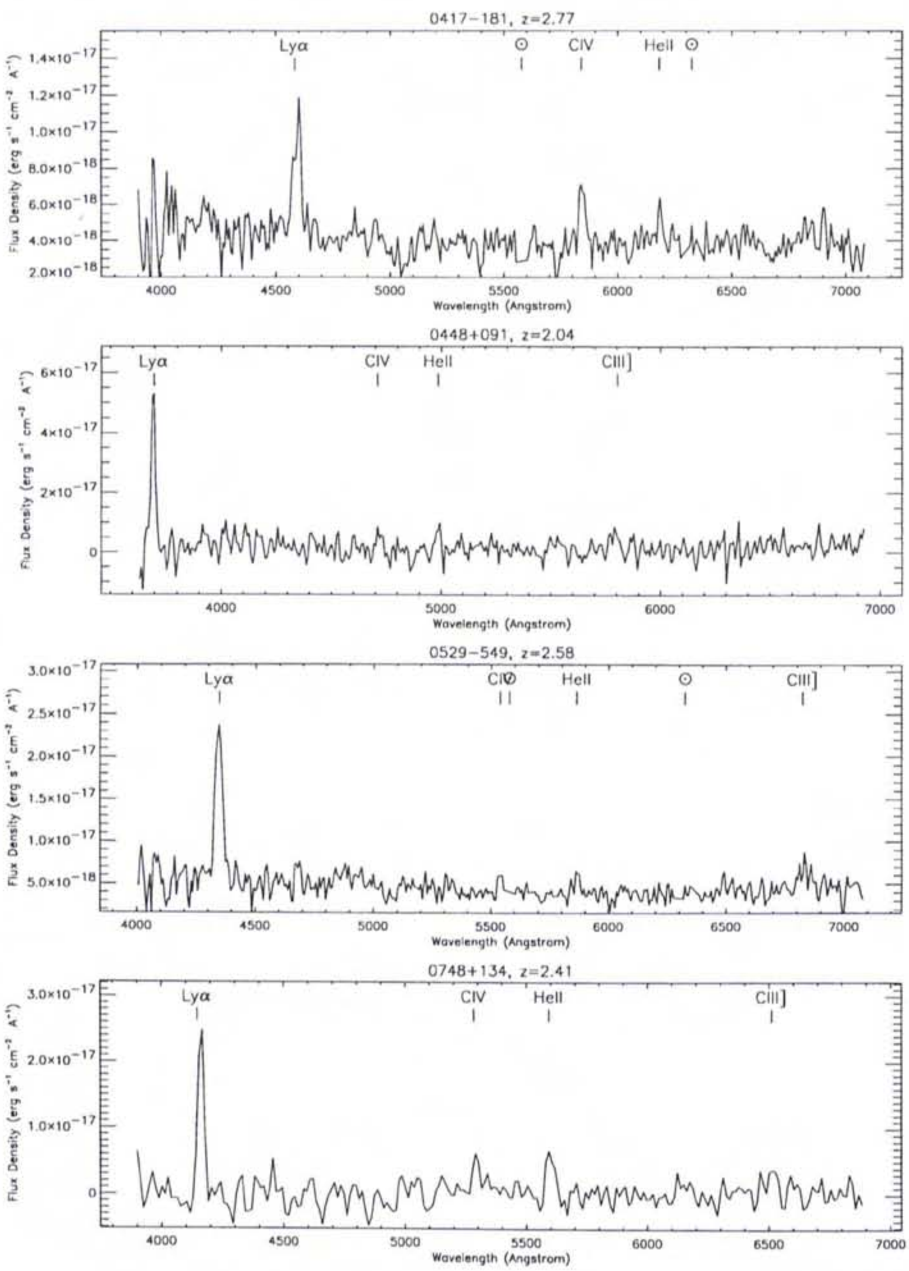

Figure 1: NTT and 3.6-m spectra of 4 z > 2 radio galaxies found during the ESO Key Programme.

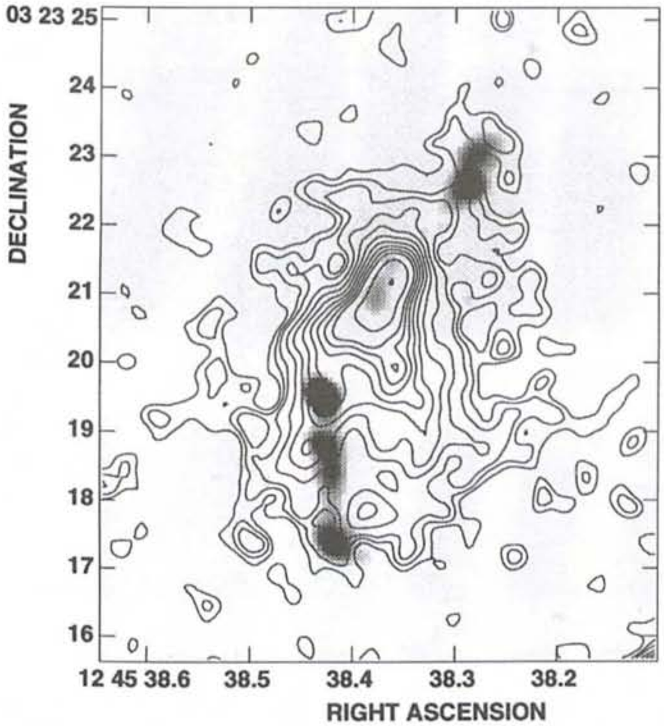

Figure 2: A contour plot of the Lyα halo of the radio galaxy 1243+036 at z = 3.6, with a grey-scale plot of the 8.3-GHz VLA map superimposed.

Programme (Miley et al., 1989; 1992). Here we shall concentrate on one of the most interesting scientific aspects of the project, namely the nature of the gas associated with many of the distant radio galaxies.

2. Lyα Emission: Clues to Galaxy Formation

One of the most remarkable features of distant radio galaxies is that they usually possess giant luminous halos of ionised gas, which can extend to > 150 kpc, with velocity dispersions of typically ~ 1000 km s^{-1}. On the arcsecond scale these halos are highly clumped. In Figure 1 we show NTT and 3.6-m spectra of $z > 2$ galaxies that were discovered during the ESO Key programme. Integration times are typically 1–2 hours. The dominant emission line in these spectra is Lyα λ1216. The Lyα emission can be as luminous as 10^{44} erg s^{-1}. Other lines that are often present, but with fainter intensities (< 10% of Lyα) are C IV, He II, C III].

One of the most spectacular high-redshift gas halos so far known is that associated with one of our Key Programme galaxies, 1243+036 at $z = 3.6$. Deep narrow-band imaging and high-resolution spectroscopy show an extended Lyα halo with complex kinematics (van Ojik, 1995; van Ojik et al., 1995a).

The Lyα halo of 1243+036 has a luminosity ~ $10^{44.5}$ ergs s^{-1} and extends over ~ 20″ (135 kpc). The Lyα image (Figures 2 and 3) shows that the emission-line gas is aligned with the main axis of the radio source and has structure down to the scale of the resolution. High-resolution spectra show that the Lyα emitting gas has a complex kinematic structure (Fig. 4). The gas contained within the radio structure has a relatively high velocity width (~ 1500 km s^{-1} FWHM). The component of the Lyα emission that coincides with the bend in the radio structure is blueshifted with respect to the peak of the emission by 1100 km s^{-1}. There is low surface brightness Lyα emission aligned with, but extending 40 kpc beyond both sides of the radio source. This halo has a narrow velocity width (~ 250 km s^{-1} FWHM) and a velocity gradient of 450 km s^{-1} over the extent of the emission. The presence of the quiescent Lyα component aligned with the AGN axis, but outside the radio source, is strong evidence that photoionisation by anisotropically emitted radiation from the active nucleus is occurring. Because the halo extends beyond the radio structure with less violent and more ordered kinematics than inside the radio structure, we conclude that the outer halo and its kinematics must predate the radio source. The ordered motion may be large-scale rotation caused by the accretion of gas from the environment of the radio galaxy or by a merger. Although alternatively the halo may be caused by a massive outflow, we argue that bulk inflow of the emission line gas is inconsistent with the most likely orientation of the radio source.

The large velocity-width of the Lyα gas contained within the radio source compared to that of the outer halo suggest a direct interaction of the radio source with the gas. The spatial correlation of enhanced, blueshifted Lyα emission and the sharp bend of the radio structure suggest that the emission-line gas could have deflected the radio jet. The impact of the jet could have accelerated the gas at this position and may have locally enhanced the Lyα emission.

3. Lyα Absorption: A New Diagnostic of High-Redshift Neutral Gas

Another unexpected discovery which came as a direct result of studying the properties of the Key Programme radio galaxies is that deep narrow troughs often "disfigure" the Lyα profiles. High-resolution spectra show that in some cases these features are too sharp to be

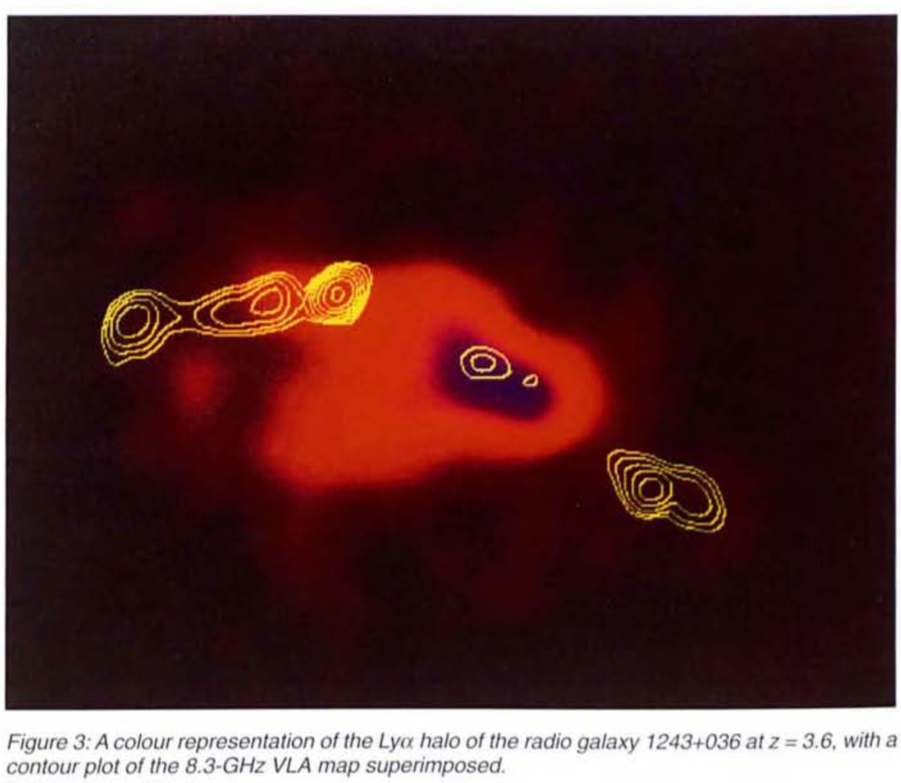

Figure 3: A colour representation of the Lyα halo of the radio galaxy 1243+036 at z = 3.6, with a contour plot of the 8.3-GHz VLA map superimposed.

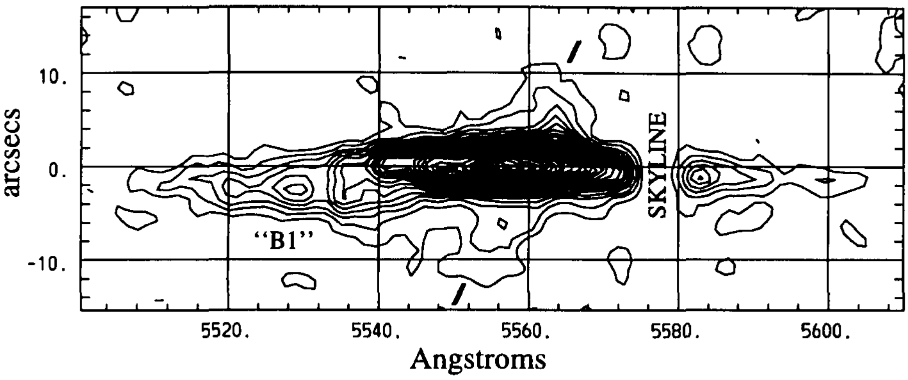

Figure 4: A two-dimensional representation of the 2.8 Å resolution spectrum of Lyα of 1243+036 (z = 3.6) taken through a slit oriented along the main axis of the radio emission.

explained as separate kinematic components of the emission, but that they are definitely due to absorption by neutral hydrogen in the line of sight. An example is provided by the Key-Programme radio galaxy 0943—242 at z = 2.9 (Röttgering et al., 1995). A spectrum of the Lyα profile (Fig. 5) reveals a complex emission line profile which is dominated by a narrow trough centred 250 km s^{-1} blueward of the emission peak and which appears as a "bite" out of the spectrum. The obvious interpretation is that it is due to H I absorption. The necessary column density is 1×10^{19} cm^{-2}. Because the absorption is so deep, it must cover the entire Lyα emission region, which has a spatial scale of 1.7″. The linear size of the absorber is thus at least 13 kpc. This was the first direct measurement of the spatial scale of an absorber with a column density of ~ 10^{19} cm^{-2}.

We have now analysed deep high-resolution spectra for a sample of 18 distant radio galaxies (van Ojik, 1995; van Ojik et al., 1995b). Most of the spectra were taken using the EMMI-spectrograph on the NTT with integration times of a few hours. H I absorption features appear widespread in the Lyα profiles. 11 radio galaxies of the sample of 18 have strong (> 10^{18} cm^{-2}) H I absorption.

Since in most cases the Lyα emission is absorbed over the entire spatial extent (up to 50 kpc), the absorbers must have a covering fraction close to unity. Given the column densities and spatial scales of the absorbing clouds, the typical H I mass of these clouds is ~ 10^8 $M_\odot$.

The Lyα absorption provides a new diagnostic tool for studying and spatially resolving neutral gas at high redshifts. Because the spatial extension of the absorbing region can be studied, the Lyα absorption can provide information about the properties of the neutral gas (e.g. dynamics and morphologies) which cannot be studied using quasar absorption lines.

4. Interaction with the Radio Sources: Nature of the Gas

There are several pieces of indirect evidence from the Lyα emission data that high redshift synchrotron jets have a strong influence on the gas through which they propagate. The gas associated with larger radio sources (> 50 kpc) tends to have (i) larger Lyα sizes, (ii) smaller velocity dispersions and (iii) less likely to undergo Lyα absorption than the gas associated with smaller radio sources. There are also correlations between the distortions in the two-dimensional Lyα spectra and the complexity of the radio structure which implies a link between the radio structure and the gas kinematics.

In addition to these statistical arguments, the data on 1243+036 presented above provides a compelling direct example that the jet-gas interaction can be vigorous enough to bend the jet.

The general properties of both the Lyα absorption and emission data can be explained qualitatively as being produced by different regions within a single large gaseous structure. Three different scenarios can be invoked to explain the observed correlations between the radio and gas properties. They are based on differences in (i) orientation of the system with respect to the line of sight, (ii) evolutionary stage and (iii) properties of the environment, with the smaller radio sources being situated in denser environments than the larger radio sources.

Considering the filling factors and physical parameters derived from our Lyα observations, we estimate that a gas halo has a characteristic mass of ~ 10^9 $M_\odot$, and is typically composed of ~ 10^{12} clouds, each having a size of about 40 light-days, i.e. comparable with that of the solar system. It is tempting to speculate that these clouds are intimately associated with the early formation stages of individual stars and that they delineate a fundamental phase in galaxy evolution.

5. The Formation of Galaxies

An ultimate aim of studying high-redshift galaxies is to constrain models of galaxy formation. Recent observational evidence suggests that distant radio galaxies may well be proto-cD galaxies. Deep continuum images with the HST show that a radio galaxy at z = 3.8 (4C41.17) is composed of many (> 20) distinct sub-kiloparsec clumps distributed within a 100 kpc Lyα halo. These clumps may be undergoing vigorous star formation (van Breugel, 1996; van Breugel et al., 1996).

We have suggested that the ordered motion in the giant gas halos surrounding 1243+036 (Figs. 2, 3 and 4) may well be due to rotation of a protogalactic gas disk at z = 3.6 out of which the galaxy associated with 1243+036 is forming. A gravitational origin of the rotation of such a large disk implies a mass of ~ $10^{12} \sin^{-2}(i)$ $M_\odot$, where i is the inclination angle of the disk with respect to the plane of the sky. Such a picture would be consistent with some current galaxy formation models. For example, numerical simulations by e.g.

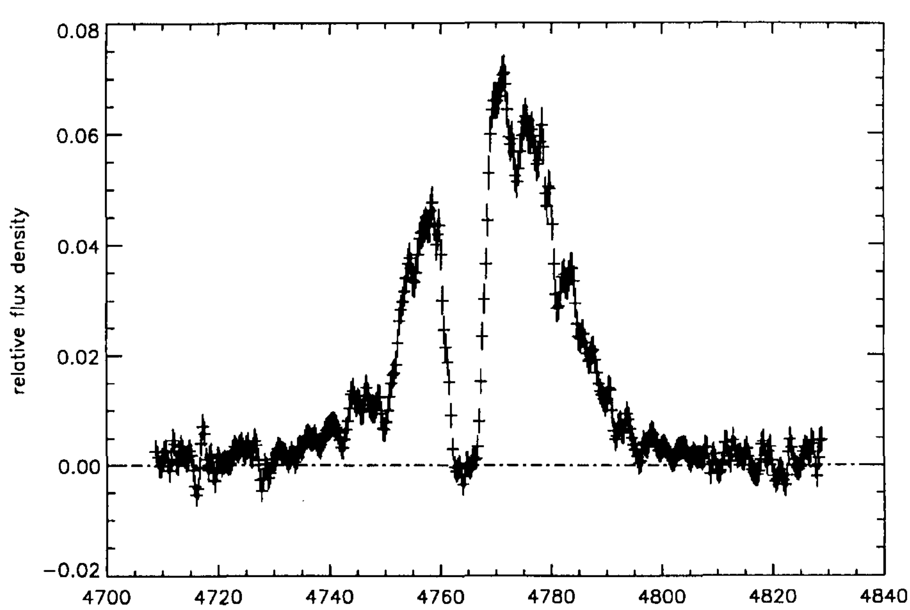

Figure 5: Part of the high-resolution spectrum (1.5 Å) of the Lyα region of the z = 2.9 radio galaxy 0943–242. (see also Röttgering et al., 1995).

Evrard et al. (1994) using hierarchical clustering scenarios indicate that rotating disks with radii of several tens of kiloparsecs should be common around forming galaxies at high redshift.

6. The VLT and the Next Decade

Because of their unique diagnostic abilities, high-redshift radio galaxies are among the most important targets both for the HST and the next generation of large optical-IR telescopes, including the VLT. The VLT should allow the enigmatic outer fainter regions of the galaxies to be mapped and the spatial extensions in some of the weaker emission lines to be measured, thereby providing new diagnostics on the state of the gas.

Here we have concentrated on discussing the gaseous properties of high-redshift galaxies. Studies of stars, dust and synchrotron emission are of course also essential if the history of the galaxy formation is to be pieced together. High spatial resolution images and spectra will measure spectral energy distributions and polarisations for the nuclear regions and continuum clumps, while the kinematics and morphological distribution of the gaseous clumps should provide clues to whether and how the observable gas is being converted into stars.

Not only are distant radio galaxies interesting in their own right as laboratories for studying galaxy formation, but their environments are particularly intriguing regions of the Universe to examine in detail. Such topics are outside the scope of the present article. However, we remark that since low-redshift radio-loud objects tend to be in rich clusters of galaxies, the surroundings of high-redshift radio-loud objects are among the most fruitful places to seek the most distant clusters.

We expect that such studies will provide important new insights into the evolution of galaxies and clusters and that the VLT will play a major role in this exciting work.

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E-mail address: Huub Röttgering, rottgeri@reusel.strw.LeidenUniv.nl

Proper Motions of Galaxies – the Reference Frame

C. TINNEY[1], G. DA COSTA[2] and H. ZINNECKER[3]

[1]Anglo-Australian Observatory, [2]Mount Stromlo and Siding Spring Observatories, [3]Astrophysikalisches Institut Potsdam

Introduction

CCD astrometry offers the possibility of measuring proper motions for the nearest galaxies, either from the ground or using HST, in only 5–10 years. An inertial reference frame, however, is needed against which to measure these motions. We have therefore been using the La Silla telescopes to seek QSOs behind several of the nearest satellite galaxies of the Milky Way, using a variety of techniques.

The Prospects for Proper Motions

In a previous Report, Tinney (1993) discussed some of the features which make CCDs almost ideal detectors for small-angle, relative astrometry at extremely high precisions (i.e., 110 mas). In particular, it was suggested that an astrometric programme targeted at the nearest galaxies could be fruitful.

Since then, observations at two epochs (May and June 1994) of a field in the globular cluster NGC 6752 have been successfully carried out in excellent seeing (better than 0.5″) using SUSI on the NTT. These observations were centred on the known QSO Q1908-6002, and aimed to both test the astrometric limits to which SUSI could be pushed, and to measure the proper motion of NGC 6752 over a baseline of 18 months. Eighty-two reference stars were selected, based on their colour-magnitude diagram membership of the cluster, and used to define a linear transformation (with an allowed rotation) from a single frame in the first epoch to each of rest the frames. The typical one-sigma residuals in α and δ about these transformations were only 3.5 and 4.2 mas (respectively). This means that the position of a single object (i.e. the reference QSO) could be determined in α and δ at a single epoch to within 1.8–2.1 mas. This essentially confirms the expectation that the NTT/SUSI combination will be ideal for high-precision astrometry, and means that with observations carried out every other year over a six-year period, proper motions can be measured to ±0.2 mas/year*.

The Search for Reference Objects

It is therefore clear that, technically, there is no reason why proper motion programmes for the nearest satellite galaxies of the Milky Way (which are expected to have proper motions of 0.5–2 mas/year) can't be begun now. And scientifically, the rewards from such a programme would obviously be of incredible value to our understanding of the dynamics of the Local Group, the forma-

*Unfortunately, no subsequent observations of this field have yet been obtained in sufficiently good seeing to actually produce a proper-motion estimate for NGC 6752.