Variable 21cm absorption at z=0.3127

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ABSTRACT
We report multi-epoch GMRT HI observations of the $z = 0.3127$ damped absorber towards the quasar PKS 1127-145, which reveal variability in both the absorption profile and the flux of the background source, over a time-scale of a few days.

The observed variations cannot be explained by simple interstellar scintillation (ISS) models where there are only one or two scintillating components and all of the ISS occurs in the Galaxy. More complicated models where there are either more scintillating components or some of the ISS occurs in the ISM of the $z = 0.3127$ absorber may be acceptable. However, the variability can probably best be explained in models incorporating motion (on sub-VLBI scales) of a component of the background continuum source, with or without some ISS.

All models for producing the variable 21cm absorption profile require small scale variations in the 21cm optical depth of the absorber. The length scale for the opacity variations is $\sim 0.1$ pc in pure super-luminal motion models, and $\sim 10$ pc in pure ISS models. Models involving sub-luminal motion, combined with scintillation of the moving component, require opacity variations on far smaller scales, $\sim 10$ – 100 AU.

Key words: Cosmology : observations – 21cm, variability

1 INTRODUCTION
The flat spectrum radio-loud quasar PKS 1127-145 ($z \sim 1.187$) is known to vary at many wave bands and over widely differing time scales. Long term flux monitoring (e.g. Wehrle et al. 1992; Bondi et al. 1994) has shown that its flux at several radio frequencies varies on time scales ranging from days to months. The source is an intra-day optical variable (Romero, Cellone & Combi 1999). It has also been detected in the X-ray (Siebert et al. 1998) and the gamma-ray bands (Thompson et al. 1994). At energies > 100MeV, EGRET observations found flux variations between the two epochs of observation (McLaughlin et al. 1998).

Sub-millisecond imaging of PKS 1127-145 at 15 GHz (Kellermann et al. 1998) has shown that it has a simple core-jet structure, with a prominent knot at the location of a sharp bend in the jet. This core-jet structure is also seen in VLBI observations at lower frequencies (Tingay, Murphy & Edwards 1998; Bondi et al. 1996). Multi-epoch VLBI observations at 1.67 GHz (Bondi et al. 1996) showed a strong increase in both the flux density as well as the compactness of the core at the third epoch, suggestive of the emergence of a new component.

Damped Lyman-α absorption was detected at $z \sim 0.3127$ towards PKS 1127-145 by Rao & Turnshek (1999), using the Hubble Space Telescope. The column density of the absorbing system was found to be quite high, $N_{HI} = 5.1 \times 10^{21}$ per cm$^2$. Optical observations have so far been unable to provide an unambiguous identification of the absorber, as there are three galaxies close to the line-of-sight, at redshifts very similar to that of the damped absorption (Lane et al. 1998; Bergeron & Boisse 1991). 21cm absorption was also detected from this $z = 0.3127$ system by Lane et al. (1998), using the Westerbork Synthesis Radio Telescope (WSRT). Higher sensitivity Giant Metrewave Radio Telescope (GMRT) observations (Chengalur & Kanekar 2000) showed that the absorption profile has a number of narrow components, spread out over a velocity range of $\sim 100$ km s$^{-1}$.

We report here on multi-epoch GMRT observations of this 21cm profile. As described in section 2 below, the 21cm absorption profile is observed to vary on a timescale of a few days. This is the second extra-galactic 21cm absorber to show variability, the other system being the $z \sim 0.524$ damped absorber towards the BL Lac object AO 0235+164 ( Wolfe, Briggs & Jauncey 1982). We discuss, in section 3 models which might produce the observed variations.
2 OBSERVATIONS AND RESULTS

PKS 1127-145 was observed with the GMRT at 8 epochs during April–May and September–October 1999. The backend used was the 30 station FX correlator, configured to give 128 channels over a total bandwidth of 1 MHz, i.e. a channel spacing of $\sim 7.8$ kHz (or $\sim 2$ km s$^{-1}$). The number of antennas used for the observations varied between 7 and 12. The varying baseline coverage is, however, of no consequence since PKS 1127-145 is an extremely compact source (angular size $\lesssim 15$ milliarcseconds) and is not resolved by even the longest baselines of the GMRT. The observing details are given in Table 1.

Flux and bandpass calibration were carried out using 3C286, which was observed at least every 40 minutes during each observing session. The data was converted from the telescope format to FITS and analyzed in AIPS using standard procedures. The task UVLIN was used to subtract the continuum emission of the background quasar; maps were then produced and spectra extracted from the three-dimensional data cube. Spectra from different days were corrected to the heliocentric frame, scaled to the same flux level, and then combined to produce the final averaged spectrum.

The lower panel of Figure 1 shows the final spectrum, averaged over the 8 epochs of observation; here, flux is plotted against heliocentric velocity, centered at $z = 0.3127$. All spectra were scaled to a common continuum flux of 6.3 Jy, before they were combined together, i.e. the y-axis is effectively the optical depth. The RMS noise level on the spectrum (note that this is computed from absorption-free regions in the final averaged spectrum) is $\sim 3.5$ mJy. The upper panel of the figure shows the RMS across the eight epochs of observation, plotted as a function of heliocentric velocity. It can be seen that the noise levels are far higher at line locations than in absorption-free regions, as would be expected for a time-variable absorption profile. Figure 3 shows a plot of difference spectra, obtained by subtracting the final averaged spectrum from the spectra of individual epochs (each scaled to a common continuum flux of 6.3 Jy; the y-axes are thus effectively the differential optical depth). The average spectrum is also plotted on the two lowest panels, for comparison. Note that the scale on the difference spectra has been expanded by a factor of 10 as compared to that on the average spectrum. Finally, the $3\sigma$ noise on each difference spectrum (computed in absorption-free regions) is indicated on the left, by the vertical barred lines.

An examination of figure 2 shows that the variation of different components is not synchronized, i.e. the observed variability is not due to some simple problem in the scaling of the continuum flux. There is no evidence for interference corrupting the spectra. Since the spectra show a measurable Doppler shift over the period of observation, an interference signal, which would stay at a fixed frequency, would be easy to pick out. At all our observing epochs, we have observed both polarizations; the spectra from the two polarizations (which are processed through largely independent receiver chains) are identical to within the noise. On one epoch (10th May 1999), we have two contiguous observations with the line profile shifted by a non-integral number of channels; the profiles obtained from these two observations are again identical within the noise. Finally, we have verified through simulations that the observed variations are not the result of finite channel resolution.

Fitting of multiple Gaussians to the average spectrum and to the spectra of individual epochs shows that the changes in the profile are consistent with variations in only the depths of the various components, with no changes in their positions or widths. A total of nine Gaussians were fit to the final spectrum. Although the changes in the depths of some of the components were found to be correlated (notably the three deepest components in Figure 3), not all the components vary in a correlated manner. The observed variations in the 21cm profile of the $z = 0.524$ damped absorber towards AO 0235+164 (Wolle et al. 1982) can also be similarly explained by changes solely in the amplitudes of individual components of the profile (i.e. with no changes in their centroids or widths). Note that although those authors quote a characteristic time scale of 6 months for changes in the $z = 0.524$ absorber, examination of Figure (5) in Wolfe et al. (1982) shows statistically significant differences between spectra taken as little as 2 days apart.

Table 2 also lists the measured flux values of PKS 1127-145 for each observing session, along with error bars. The fluxes are found to vary widely, with values ranging from $\sim 4.0$ Jy to $\sim 7.9$ Jy. The most dramatic change is between the 8th and the 10th of October, a flux increase of 1.8 Jy over two days. Our experience with the GMRT indicates that the flux calibration is reliable to $\sim 15\%$, in this observing mode.

3 DISCUSSION

As described above, the observed 21cm optical depth ($\tau_{21}$) of the $z = 0.3127$ absorber varies over timescales of a few days. A change in the observed optical depth could arise from a number of reasons: (1) changes in the physical conditions (i.e. spin temperature, column density) in the absorber, (2) inter-stellar scintillation of one or more components of the background source and (3) motion of a source component across the sky so that the line-of-sight to this component traces regions of different opacity. We will, in this section, discuss each of the above possibilities in greater detail. Models for producing the variable 21cm absorption towards AO 0235+164 are discussed by Briggs (1983).

The short timescales involved make it very unlikely that the observed variability originates in changes in the column density along the line-of-sight, arising from motion of the absorbing clouds. Even if one assumes that the characteristic scale on which the opacity varies is 20 AU (see below) and that the absorption occurs against a highly compact background source, variations over a timescale of 2 days would require the absorbing material to have transverse velocities of $\sim 0.1c$. This is quite unrealistic for cold gas in a galaxy or for tidal debris. Similarly, there is no plausible mechanism for recurrent changes of the spin temperature of a cloud of this size over a timescale of days. We hence do not consider this model further.

Changes in the line profile could be explained if some part of the background continuum flux arises from a region of such small angular size that it gives rise to inter-stellar scintillation (ISS) (Dennett-Thorpe & de Bruyn 2000; Rick-
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Table 1. Observing details.

| Observation epochs (1999) | Centre frequency (MHz) | Flux density\(^a\) (Jy) |
|---------------------------|------------------------|-------------------------|
| 27 Apr                    | 1082.000               | 5.2 ± 0.8               |
| 6 May                     | 1082.000               | 7.9 ± 1.2               |
| 10 May                    | 1082.049               | 6.1 ± 0.9               |
| 10 May                    | 1081.949               | 6.0 ± 0.9               |
| 17 May                    | 1081.949               | 7.0 ± 0.4               |
| 22 Sep                    | 1082.050               | 4.0 ± 0.6               |
| 8 Oct                     | 1082.050               | 4.3 ± 0.6               |
| 10 Oct                    | 1082.050               | 6.1 ± 0.9               |
| 15 Oct                    | 1082.050               | 7.4 ± 1.1               |

\(^a\)The errors quoted include systematic errors, based on earlier GMRT observations of standard calibrators in this observing mode.

Figure 1. The lower panel shows the final averaged spectrum towards PKS 1127-145 plotted versus heliocentric velocity, centred at \( z = 0.3127 \). The RMS noise level is plotted in the upper panel.

Figure 2. Difference spectra on the 8 epochs of observation, plotted as a function of heliocentric velocity, centred at \( z = 0.3127 \). The panels are labelled by the dates of observation. The lowest two panels contain the final averaged spectrum, for comparison. Note that the scale on the y-axis is expanded for the difference spectra. The 3\( \sigma \) noise on each difference spectrum (computed in absorption-free regions) is indicated on the left, by the vertical barred lines.

Kedziora-Chudczer et al. 1997 (Kellermann et al. 1998) have shown that it has a simple core-jet structure in 15 GHz VLBI observations of PKS 1127-145. The lack of correlation between the variations in flux and opacity rule out the simplest such models.
structure. The core is unresolved at sub-milliarcsecond resolution. The simplest scintillation model is that of a single compact scintillating component in the core, with the rest of the flux not giving rise to scintillation. In this case, however, two epochs with the same observed continuum flux should have the same observed spectrum; further, the line depths should be deeper at epochs of higher flux and vice versa. Table (1) shows that the flux values agree within the error bars on the 22nd of September and the 8th of October; however, the spectra at these epochs are considerably different. Similarly, the background flux is the same on the 10th of May and the 10th of October while the spectra are again quite different. Given our error bars, the flux change required to produce the observed differences in the 21cm spectra would have been easily detectable, unless the line-of-sight to the scintillating component also coincidentally spectra would have been easily detectable, unless the line-of-sight to the scintillating component also coincidentally happened to have an optical depth of order unity. The latter situation is also, however, not viable since the epoch with the highest background flux ($S = 7.9 \pm 1.2$ Jy, on the 6th of May) has the weakest absorption. Thus, the simplest ISS model appears to be ruled out.

The next simplest ISS model is one in which there are two scintillating components and a steady component. The second scintillating component could, for example, arise in the bright unresolved knot in the jet of PKS 1127-145, which is separated from the core by ~2.5 milliarcseconds. If the optical depth towards each of the scintillating components is comparable to the average optical depth over the entire source (i.e. $\tau_{21} \sim 0.1$) then, as discussed below, this model is also ruled out by the data of 22nd September and 8th October. The difference spectrum on 8th October consists of two components which are ~50 mJy deeper than the average spectrum and three which are ~30 mJy deeper than the average. On the 22nd of September the first two components are weaker (by ~30–40 mJy) than the average, while the remaining three agree (within the noise) with the average spectrum. If one assumes that the absorbing clouds are distributed such that the changes in the first two line components arise from one of the scintillating source components (total change in line depth, $\Delta S \sim 90–100$ mJy, per component) and the changes in the remaining three stem from the other (total change in line depth, $\Delta S \sim 30–40$ mJy, per component), the changes in line depth would correspond to a flux change of at least 1.3 Jy (for $\tau_{21} \lesssim 0.1$), which is not seen (other distributions of the clouds would exacerbate the problem). Since these two compact components contain far more than 10% of the total flux, it is rather unlikely that the optical depth in front of the scintillating components is $\sim 1$, while the average optical depth is $\sim 0.1$.

One could construct more complicated models, wherein each of the compact VLBI components contain more than one scintillating component. The relation between the observed spectrum and the measured flux becomes more and more complex with an increasing number of scintillating components and it would hence be possible to contrive situations where both the variations might be explained purely as a result of ISS in the Galaxy. However, from the Taylor-Cordes (1993) model of the distribution of ionized gas in the Galaxy, the scatter broadening expected towards PKS 1127-145 is 0.4 milliarcseconds. It thus seems unlikely that uncorrelated ISS would result, even if the core or knot has multiple compact components. We note, however, that ISS might also occur in the galaxy(ies) giving rise to the absorption at $z = 0.3127$, while all the above models only consider the case of it occurring in the Galaxy. Scintillation could prove to be a viable model if significant ISS does occur in the interstellar medium of the absorber.

Motion of a source component across the sky might explain the changes in absorption profile, if the absorbing system has opacity variations transverse to the line-of-sight. The line-of-sight to the moving component samples different paths through the absorber at different epochs, resulting in changes in the profile. Super-luminal motion on sub-VLBI scales has often been invoked to explain rapid variability of QSO fluxes (Rees 1966; Volter 1966). If these variations are intrinsic, they are difficult to explain in the standard context of incoherent synchrotron emission as causality arguments would imply brightness temperatures far in excess of the limit of $10^{12}$ K set by the inverse Compton catastrophe. Super-luminal motion of a source component produces a Doppler boosting of the observed brightness temperature by a factor $\delta^2$ over the true source brightness temperature, where $\delta$ is the Doppler factor. Thus, if $\delta$ is sufficiently large, the true brightness temperature would be lower than the inverse Compton limit. In these models, the timescale of variability can be used to place a lower limit on $\delta$. Doppler factors of order 10 are sufficient to account for the variability seen in the majority of compact sources; similar values have also been measured from VLBI observations of super-luminal motion. However, observed variations in the 1420 MHz flux of AO 0235+164 on timescales of days yield $\delta \gtrsim 100$ (Krauss et al. 1999). Similarly, long term monitoring of the flux of PKS 1127-145 at 4.8, 8.0 and 14.5 GHz (under the Michigan Monitoring program) have found short timescale variability which, if assumed to be intrinsic, would require $\delta \sim 100$. Our own continuum measurements (albeit with larger error bars) also require $\delta$ values of the same order.

As mentioned earlier, the change in absorption profile in this model also requires the absorbing system to have opacity variations transverse to the line-of-sight. The extent of inhomogeneity in the absorber can be estimated from the fact that the physical distance $l$ travelled by the moving component between two observations separated by an interval $\Delta t_{\text{obs}}$ (in the observer’s frame) is $\sim \delta c \Delta t_{\text{obs}}$, where we have assumed $\delta \approx \gamma$, the Lorentz factor. The corresponding projected distance in the absorber is $\delta \chi_{\text{obs}} (D_s/D_c)$, where $D_s$ and $D_c$ are the angular diameter distances of the source and the absorbing clouds respectively. Variations in the line profile over $\Delta t_{\text{obs}} \sim 2$ days would require the absorbers to have opacity variations on similar scales, i.e. $\sim 1.6 \times 10^{-3} \delta (D_c/D_s)$ parsecs. Using the source and absorber redshifts in a flat, matter-dominated FRW cosmology (with $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$) yields $D_c \sim 775$ Mpc and $D_s \sim 1184.5$ Mpc. The absorbers must thus be inhomogeneous on length scales of ~0.1 parsecs to explain the changes in the line profile in the above model. (Note, however, that the coherence scale of velocities in the absorber must be much larger, to account for the unchanged positions of the velocity centroids of individual line components.)
The Doppler factors required in this scenario are, of course, rather large but might be explicable in shock-in-jet models \( [\text{Marscher \\& Gear 1985; Qian et al. 1991; Blandford \\& Konigl 1979}] \), which are variants of the standard relativistic beaming paradigm.

Sub-luminal motion of a source component could also explain the variations in both the flux and line profile, if the moving component was sufficiently small so as to give rise to interstellar scintillation. Of course, there would be no correlation between the measured flux and the line profile in this situation, since the line-of-sight to the scintillating component would itself change. This scenario would, however, require the absorbing clouds to have structure on very small scales. For example, speeds of the order of 0.1 \( c \) (at \( z = 1.187 \)) would imply changes in opacity on scales of \( \sim 20 \) AU, at the redshift of the absorber, to account for the changes in line profile over two days. Such line structure in HI opacity, on scales of \( 10 – 100 \) AU, has, in fact, been seen earlier in our Galaxy, inVLBI 21cm absorption studies \( [\text{Faison et al. 1998; Frail et al. 1994}] \). In fact, these observations have found the optical depth in the Milky Way to vary by a factor of two, over the above length scales; this is more than sufficient to explain the changes seen in the absorption profile of the \( z = 0.3127 \) absorber. We note in passing that several spin temperature measurements, in particular those of damped Lyman-\( \alpha \) systems would become suspect, should \( 10 – 100 \) AU be the typical size scale of HI “clouds”. As emphasized by Deshpande (2000), however, opacity variations on scales of \( 10 – 100 \) AU do not necessarily imply the existence of physically distinct extremely dense clouds of this size. If these variations are only random opacity fluctuations on small scales, with a much weaker systematic gradient in opacity, the spin temperature measurements are probably reliable.

The final model we mention is one where gravitational microlensing of a moving background component by stars or stellar clusters in the \( z = 0.3127 \) absorber gives rise to variations in both the flux and the line profile \( (\text{Gopal-Krishna \\& Subramanian 1991}) \). Microlensing causes the apparent transverse velocity of a moving component to increase; this would, in turn, increase the length scale on which opacity variations are required to exist in the absorbing source. Microlensing scenarios are strongly dependent on the geometry and structure of both the source and the lens. Further, a source which is compact enough for micro-lensing to be important would probably also give rise to ISS; we will hence not explore any detailed microlensing models here. We note, however, that microlensing is a likely scenario, given the fact that an absorbing galaxy lies along the line-of-sight to the background quasar; simultaneous multi-frequency observations could be used to test the presence of microlensing, due to the achromatic nature of this phenomenon.

In summary, while there are a number of models which could produce the observed variability in both the flux and the 21cm profile, all models require the optical depth of the absorber to have small scale structure. The length scale for the opacity variations is \( \sim 0.1 \) pc in pure super-luminal motion models, and \( \sim 10 \) pc in pure ISS models. Models involving sub-luminal motion, combined with scintillation of the moving component, require opacity variations on far smaller scales, \( \sim 10 – 100 \) AU.

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