An Optical Velocity for the Phoenix Dwarf Galaxy\textsuperscript{1}

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ABSTRACT

We present the results of a VLT observing program carried out in service mode using FORS1 on ANTU in Long Slit mode to determine the optical velocities of nearby low surface brightness galaxies. As part of our program of service observations we obtained long-slit spectra of several members of the Phoenix dwarf galaxy from which we derive an optical helio-centric radial velocity of $-13 \pm 9$ km/s. This agrees very well with the velocity of the most promising of the HI clouds seen around Phoenix, which has a helio-centric velocity of $-23$ km/s, but is significantly different to the recently published optical heliocentric velocity of Phoenix of $-52 \pm 6$ km/s of Gallart \textit{et al.} (2001).

\textit{Subject headings:} GALAXIES: INDIVIDUAL: PHOENIX, GALAXIES: KINEMATICS AND DYNAMICS, GALAXIES: LOCAL GROUP

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1. Introduction

Dynamical measurements of outlying Local Group galaxies are crucial for constraining both the age and the total mass of the Local Group and for probing the nature of the intrinsic dark matter within the galaxies. A necessary part of this process involves investigating the link between possible HI detections, the optical components of the galaxies and the relevance of the HI to the recent star formation history of the system. Optical velocities determine if observations of HI gas in and around these systems are the result of gas associated with these galaxies, a chance superposition with high velocity HI clouds, outlying components of the Magellanic Stream, or just Galactic foreground contamination.

Phoenix is a member of the Local Group, lying about 450 kpc from our Galaxy (Ortolani & Gratton 1988) in a fairly isolated location on the opposite side of the Galaxy from the Andromeda sub-system (see Table 1). It is possibly one of the most distant of the satellites of our Galaxy, or perhaps a free-floating outlying Local Group object. It appears to be a galaxy in transition between a dwarf irregular (dI) and a dwarf spheroidal (dSph) system, having had both a recent burst of star formation and a plausible detection of $\approx 10^5 M_\odot$ of HI. The HI gas has been detected close to the position of Phoenix at several different locations, and velocities ($v_\odot = 56 \text{ km/s}, 120 \text{ km/s}$ Carignan, Demers & Côté 1991; $v_\odot = -23 \text{ km/s}$ Oosterloo, Da Costa & Staveley-Smith 1996; and from mosaic mapping using the Australia Telescope Compact Array at $v_\odot = -23, 7, 59, 140 \text{ km/s}$ St-Gérmain et al. 1999). Due to the superior resolution/sensitivity we adopt the latter measurements as defining the possible HI-associated gas throughout the remainder of this paper.

The HI complex at $v_\odot = 140 \text{ km/s}$ is thought to be an outlying component of the Magellanic Stream, which passes close to the line-of-sight of Phoenix, while the component at $v_\odot = -7 \text{ km/s}$ is undoubtedly Galactic in origin. This leaves two remaining HI components which may be associated with Phoenix. The more compact of the HI clouds at $v_\odot = -23 \text{ km/s}$ is centred about 5 arc-minutes to the southwest of the optical centre of Phoenix and overlaps the optical image. This is within a distance of about 650 pc if it lies at the same distance as Phoenix, and partially covers the optical image which is about 1 kpc in size. The component with $v_\odot = 59 \text{ km/s}$ is much more extended, fragments into four substructures, and is located significantly further to the south of the optical centre. From the HI morphology and dynamics while it is unclear whether or not the 59 km/s component is, or perhaps was in the past, associated with Phoenix, the evidence for the $-23 \text{ km/s}$ system is more compelling. The derived HI mass of $\approx 10^5 M_\odot$ is comparable to that found in the Sculptor dwarf spheroidal and in the dwarf irregular/dwarf spheroidal transition object LGS 3 (Young & Lo 1997). Furthermore, as St. Gérmain et al. point out, the HI velocity field of the $-23 \text{ km/s}$ component shows clear evidence of a velocity gradient
indicating either rotation, or ejection, from Phoenix.

The resolved stellar population of Phoenix has been studied in some detail (Ortolani & Gratton 1988; van de Rydt, Demers, & Kunkel 1991; Held, Saviane & Momany 1999; Martínez-Delgado, Gallart & Aparicio 1999; Holtzmann, Smith & Grillmair 2000). Phoenix has obviously experienced recent star formation as can be seen from the sprinkling of blue stars across the field. They are concentrated in “associations” near the centre of the galaxy and elongated in the direction of the HI cloud at $-23\text{km/s}$. This recent “episode” of star formation has been quantified by Held et al. (1999) to have started at least 0.6 Gyr ago, but accounts for less than 6% of the V-band luminosity of Phoenix and 0.2% of the mass. This is thus broadly consistent with the comprehensive modelling of the central region of Phoenix based on HST data by Holtzmann et al. (2000). They found that star formation has been roughly continuous over the lifetime of Phoenix, with no obvious evidence for strongly episodic star formation, although a mildly varying star formation rate can fit the data.

Recently in an attempt to probe the optical–HI link further, Gallart et al. (2001) published the first optical radial velocity study of a sample of 31 individual stars in Phoenix using VLT/FORS1 in MOS mode. Studying the blue end of the optical spectra in the range $\approx 3500-6000\text{Å}$, which encompasses the Mg$b$ absorption complex, they determined a mean value of $v_{\odot} = -52 \pm 6\text{ km/s}$. There is quite a large offset between this optical measurement and the most likely HI gas velocity component at $-23\text{ km/s}$. Gallart et al. interpret this difference as either caused by ejection of gas due to supernovae from the most recent burst of star formation in Phoenix about 100 Myr ago, or as a consequence of ram pressure stripping by a hot intergalactic medium within the Local Group.

The putative association of the HI gas with the optical galaxy is quite a crucial measurement, not only because of the direct coupling of the (potentially) recently expelled gas, but also because of the unique position of Phoenix in the Local Group as potentially (by far) the furthest outlying satellite of the Galaxy. At a Galacto-centric distance of $\approx 450\text{kpc}$, Phoenix could have unprecedented leverage in constraining the mass of the Galactic Halo out to 450 kpc.

As part of a long term VLT service programme to measure the radial velocities of several outlying Local Group satellites we recently acquired some service observations of Phoenix and decided that it was worth re-investigating the optical–HI connection with an additional optical velocity measurement. In this paper we therefore present the results of VLT/FORS1 long slit observations of Phoenix in the spectral region centred on the Ca II near infra-red triplet. The slit position was aligned with 7 stars bright enough to derive radial velocities from. Although this is a much smaller number of stars than observed by
Gallart et al., each spectrum is of sufficiently high S/N (≈10:1 per continuum Å) to derive an accurate velocity measurement.

2. Observations

The observations were obtained in service-mode, with UT1/FORS1 in the Long Slit Spectroscopy (LSS) instrument set-up on the nights of 5–6 October 2000 and 31 December 2000 to 1 January 2001 (see Table 2). The FORS1 long slit spans 6.8 arc-min and was used with a slit width of 1 arc-sec and the GRIS-600I+15 grism along with the OG590 order-sorting filter, to cover the Ca II triplet wavelength region with as high a resolution as possible. With this setting the pixel sampling is close to 1Å per pixel and the resolution, as estimated from measuring the full width at half maximum of a series of unresolved night sky lines, is in the range 3.5–4Å over the wavelength range 7050–9150Å. This is the maximum resolution that can be obtained with FORS1 without resorting to a narrower slit. Although this is a wavelength range at which the FORS1 CCD (Tektronix) has reduced sensitivity it is where the red giant stars we were aiming to detect are brightest. The Ca II triplet is also a useful unblended feature to accurately measure radial velocities (e.g. Hargreaves et al. 1994) and there are abundant narrow sky lines in this region for wavelength calibration and/or spectrograph flexure monitoring.

Our observation request consisted of a single slit position, or in ESO parlance a single Observation Block (OB). The data were taken in photometric or thin cirrus conditions with a dark sky (moon phase 0.3) and generally in sub-arc-second seeing conditions (see Table 2). The OB was made up of a target observation in conjunction with a sequence of radial velocity standards (both individual K-giants and bright globular clusters, see Table 3). The K-giant radial velocity standards provided the basic velocity standardization in addition to Ca II triplet template spectra for comparison with the lower signal-to-noise dwarf galaxy spectra. By observing bright globular clusters with known radial velocities we further sought to test our methodology with data more closely resembling the primary targets. A useful by-product of this is additional template spectra to cross-correlate with the main target objects.

We determined the position of the slit on the galaxy accurately by using previous FORS1 imaging of this object (Tolstoy et al. 2000), in which we tried to hit as many bright giant branch stars, which are likely to be members of Phoenix, as possible.
3. Data Reduction and Calibration

As described in Tolstoy & Irwin (2000), we did not use the basic daytime calibrations provided for UT1+FORS1 observations to either flat-field or wavelength calibrate the data. As before we made use of archive broad I-band filter twilight flat-field frames to create a master flat-field frame, and we used the plentiful night-sky lines in this spectral region to wavelength calibrate the data. The two-dimensional non-linear wavelength distortion of the long-slit data was again found to be stable enabling us to make use of the same two-dimensional wavelength calibration of all the data for a given night. This allows us to correct the distortion of the radial velocity standards, which lack significant sky-lines due to their short exposure times. After extracting all the spectra, cross-correlation of either contemporaneously extracted sky spectra or atmospheric absorption features in the object spectra were used to correct for shifts in the zero-point of the wavelength calibration caused by spectrograph flexure or mis-centering of objects in the slit. All of our calibration and data reduction was carried out using the IRAF package. \(^1\)

The observation of the Phoenix dwarf spheroidal galaxy consisted of 3×1000s exposures. There were no measurable internal shifts found for frames within a sequence, so these were averaged with k-sigma clipping used to eliminate cosmic ray events. Full two-dimensional wavelength calibration, using the night sky lines, was then done on the combined data. The globular cluster observation was an integration of 250s which was treated in the same way as the target galaxy observations.

The position of the slit across the central region of Phoenix, taken from the FIMS file used to prepare the OBs, is shown in Figure 1. Also marked are the 7 stars clearly detected in the Phoenix spectra. The position of all the resolved objects detected in the Phoenix long-slit spectra are plotted on the Colour-Magnitude Diagram (CMD) of Phoenix (from Tolstoy et al. 2000) in Figure 2. From their location on the CMD, and also position on the slit, virtually all of the stars are high probability members of Phoenix. Three stars (1058, 899 and 496) are likely to be red giant branch (RGB) members, star 845 is probably on the asymptotic giant branch (AGB), whereas 1274 and 1328 could be evolved blue loop main sequence stars. However, 1328 and 1274 (and also 773) lie in crowded regions, and could easily be RGB stars with contaminating flux from a nearby object affecting their photometry. The identification of all the resolved objects in the slit and their location on the CMD provides an excellent independent corroboration of the optical velocity

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determinations. However, we also note that stars 1328, 773 and 1274 also lie in a region of the CMD where there is a higher probability of foreground contamination.

With the usual caveats of over interpretation of posterior statistics we can make an estimate of the likelihood of foreground contamination as follows. Phoenix is at very high Galactic latitude, b=−68.9, which together with a Galactic longitude of l=272.2 suggests that the contamination by foreground stars is likely to be very low. The radial velocity distribution of potential Galactic foreground contaminants comes from K and M dwarfs in the thin disk, thick disk and halo. In this direction the velocity dispersion of foreground stars is dominated by the $\sigma_W$ component which has a value of $\approx20\text{km/s}$, $40\text{km/s}$ and $100\text{km/s}$ for thin disk, thick disk and halo stars respectively (eg. Carney et al. 1989; Mihalas & Binney 1981). The heliocentric velocity offset of the foreground components due to the relative solar motion is $\approx11\text{km/s}$, $25\text{km/s}$ and $90\text{km/s}$ respectively. All of these populations are potential contaminants but the positive systemic velocities (and to some extent the large velocity dispersions) mitigate against significant pollution. Further constraints come from the spatial density. The Phoenix CMD was constructed over a region $7\times7$ arc-min in size and over the total magnitude and colour range of the spectroscopic observations ($18.5 < R < 21$ and $1.0 < B-R < 3.0$), has 380 stellar objects detected. Of these approximately 90–95% are expected to be stars in Phoenix (e.g. Ratnatunga & Bahcall 1985), leaving some 20–30 stars as potential foreground contamination. The long-slit used in the FORS1 observations covers 0.2% of this area therefore the expected number of random contaminating foreground stars in the slit is less than 0.1 over this magnitude and colour range. However, given that we did some prior selection of brighter stars in the above magnitude colour range by aligning the slit to include three relatively bright objects, it is possible that 1 or more of these selected brighter objects could be a foreground object. Since the expected heliocentric radial velocity of Phoenix is low, contamination by say a single disk foreground K/M dwarf (the most likely contaminant) will be both difficult to spot but conversely would also have relatively little impact on the derived systemic velocity. We discuss this issue further in section 5.

4. Extracting and Wavelength Calibrating the Spectra

For the globular clusters and dSphs, image sections summed along the spatial axis were used to identify resolved stellar, or background galaxy images, in the slit and also to define the underlying unresolved background of the dwarf spheroidal galaxy for spectroscopic extraction. Spectra for these objects plus the integrated background were then extracted in
the usual manner taking care to optimise the region chosen to represent the local sky. The computed sky spectrum was also extracted contemporaneously for later use in checking the wavelength solution systematics (see Figure 3). For the radial velocity standards and also the target objects in the long slit, contributions to systematics from slit centering is also an issue that limits the achieved final accuracy. This is reflected in the scatter ($\sigma_v \sim 5\text{km/s}$) of the derived velocities for the standards in Table 4 which is dominated by slit-centering errors and limited by the accuracy of post-reduction corrections based on atmospheric absorption lines. The details are identical to those described in Tolstoy & Irwin (2000).

Wavelength calibration was primarily based on one of the central sky spectra taken from the Phoenix data. All of the remaining extracted one-dimensional sky spectra for cluster calibration and target objects were then cross-correlated against the reference image sky spectrum, to adjust the zero-point of the wavelength solution. This enables us to monitor the stability of the wavelength solution and hence determine and track any flexure of the spectrograph. The cross-correlation of sky lines within a single two-dimensional frame gives negligible velocity shifts of $\pm1\text{−}2\text{ km/s}$ which is comparable to the juxtaposition of the wavelength calibration errors and correlation-function estimation errors. Sky lines are generally not visible in the standard star spectra so the wavelength zero-point here was checked using the main atmospheric absorption A-band.

Since we had previous observations taken with a similar setup (Tolstoy & Irwin 2000) we could make further use of our earlier cluster and standard star observations to standardise the velocity determinations. After applying all the various checks on the wavelength calibration we estimate that the final systematics of the wavelength solution are in the range $5\text{−}10\text{ km/s}$, and are mainly dominated by corrections for slit-centering errors. These are comparable to the $rms$ errors, dominated by photon noise, in the cross-correlation of the fainter target objects, but are more than adequate for the current goal.

5. Determining the Radial Velocities

The main advantages of using the Ca II triplet region for radial velocity determination are three-fold: the relative brightness and uniformity of the continuum flux from K-giants; the narrowness $\approx3\text{ Å}$ of the three Gaussian-like Ca II absorption features; and the abundance of narrow night sky lines for wavelength calibration. Although at first sight the latter might seem a significant drawback too, in practice the velocity template spectrum is only “active” over the narrow regions of $\approx10\text{ Å}$ centred on each of the triplet lines. This minimises the influence of the, on average, relatively bright sky and means that in practice it is feasible
to measure reliable cross-correlations several magnitudes below the average sky level in this region.

For all the globular cluster and dSph observations, individual resolved objects were extracted separately in an attempt to identify system members and possible foreground star, or even background galaxy, interlopers. Radial velocities were measured for all the spectra, as previously described by Tolstoy & Irwin (2000), using the standard Fourier cross-correlation package in IRAF, FXCOR, after suitable continuum removal and apodizing of the target objects. The template function consisted of the spectrum of a bright radial velocity standard with the continuum fitted and removed to give a mean level of zero for the continuum. All regions outside of the Ca II triplet lines in the template were then identically set to zero, leaving “active” only the narrow region of $\approx 10^\text{A}$ centred on each of the three absorption components.

An example of the results for Phoenix is shown in Figure 4 where the Ca II triplet is clearly visible in the target spectrum. The measured radial velocities are then corrected for: the template radial velocity offset; the topo-centric correction to a helio-centric system; and for flexure/slit mis-centering. The final results for the individual objects extracted from the spectra are listed in Table 4, including Phoenix, the radial velocity standards and the globular cluster Pal 12.

Virtually all of the extracted spectra for Phoenix have radial velocities that are consistent with membership given the likely (unknown) optical velocity dispersion of $\approx 10$ km/s. The range of observed velocities in the 7 stars is from $-31$ km/s to $+9$ km/s with a mean of $-13.4$ km/s, which compares favourably with the HI velocity of $-23$ km/s. The error in the estimate is dominated by a combination of systematic residuals, random photon noise errors and the velocity dispersion of the dwarf. Combining these error estimates leads to a standard error in the derived mean velocity of around $\pm 9$ km/s. It is interesting to note that the formal $rms$ dispersion about the mean for the 7 stars is $\sigma = 14.2$ km/s. Therefore purely on kinematic grounds, it is difficult to rule out a modest disk contamination since the expected mean radial velocity for disk stars is $+11$ km/s in this direction, with dispersion of $\pm 20$ km/s. However, as noted earlier, the converse is also true, in that contamination by one or two disk stars has little impact on the derived systemic velocity of the dwarf. As noted in section 3, the most likely foreground contaminants are the 3 relatively bright stars (773,496,1274) used for selecting the most favourable slit location. Of these, 496, lies on the RGB and is therefore unlikely to be foreground. In the worst case scenario, if the other two stars are foreground, excluding them shifts the derived optical radial velocity by $+3$ km/s, which is a negligible change relative to the inherent measuring errors of $\pm 9$ km/s.
6. Discussion

Our determination of the optical velocity for Phoenix of $-13\text{km/s} \pm 9\text{km/s}$ closely matches the most likely HI velocity for this galaxy of $-23\text{ km/s}$ derived by St-Gérmain et al. (1999). In a recent review of the impact of the VLT on Local Group Galaxies, Held (2001) quotes recent UVES measurements of giant stars in the Phoenix galaxy that agree to within a few km/s of the neutral gas velocity. It is difficult to directly reconcile these much smaller negative optical radial velocities with the $-52\text{km/s} \pm 6 \text{ km/s}$ recently determined by Gallart et al. (2001).

It is highly unlikely that Galactic foreground contamination could have affected any of the optical results significantly and the HI gas velocity result of $-23\text{ km/s}$ seems convincingly secure as argued by St-Gérmain et al. (1999). There is also unlikely to be contamination of our results from the two main tidal streams enveloping our Galaxy: the Magellanic stream and the Sagittarius Dwarf tidal stream. The Magellanic Stream is predominantly gas with no unambiguous detection of a stellar component yet reported. Therefore, while the Magellanic Stream can contaminate the gas distribution in the Phoenix direction, it is unlikely to contribute to contamination of the optical velocities. Likewise, pollution by the Sagittarius Dwarf tidal stream is also highly unlikely since the projection of its current orbit does not pass close to the line-of-sight to Phoenix.

The gradient in the distribution of young stars in Phoenix (e.g., Ortolani & Gratton 1988; Martínez-Delgado et al. 1999) suggests that the recent star formation has been moving from east to west across the central component of Phoenix in a manner consistent with self-propagating star formation theories. The youngest stars are thus spatially overlapping the position of the HI cloud at $-23\text{ km/s}$ (as originally pointed out by Young & Lo 1997). The relative position and velocity of this cloud combined with the evidence of recent star formation provides evidence that a burst of star formation can disrupt and potentially blow out gas from the centre of a dwarf galaxy, inhibiting further star formation (e.g., Dekel & Silk 1986; Mac Low & Ferrara 1999), although it is not the only possible explanation for what is seen (cf. ram pressure stripping scenarios as in Gallart et al. 2001).

However, we can conclude that our results in conjunction with those of Held (2001) unequivocally show that modest amounts, ($\approx 10^5 M_\odot$), of HI gas are associated with the Phoenix dwarf galaxy albeit somewhat offset from the optical centre of the galaxy.

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Table 1: Phoenix

| Object  | RA (J2000) | Dec      | Distance (kpc) | $M_V$ | type       | ref                               |
|---------|------------|----------|----------------|-------|------------|-----------------------------------|
| Phoenix | 01 51 06   | −44 26 42| 445 ± 30       | −10.1 | dIrr/dSph  | Ortolani & Gratton 1988          |
|         |            |          |                |       |            | van de Rydt et al. 1991          |

Table 2: The Observations

| Date       | Begin UT  | Object    | Exptime (secs) | Airmass | Seeing (arcsec) | Comments              |
|------------|-----------|-----------|----------------|---------|-----------------|-----------------------|
| 06 Oct 2000| 00:33     | HD 203638 | 1              | 1.01    | 0.85            | photometric           |
| 00:46      | Pal 12    | 250       | 1.02            | 0.60    |                 |                       |
| 01 Jan 2001| 00:34     | HD 8779   | 1               | 1.15    | 1.02            | thin cirrus           |
| 01:00      | HD 8779   | 1000      | 1.20            | 0.95    |                 |                       |
| 01:12      | Phoenix–1 | 1000      | 1.13            | 1.13    | variable seeing |                       |
| 01:30      | Phoenix–2 | 1000      | 1.14            | 0.97    |                 |                       |
| 01:48      | Phoenix–3 | 1000      | 1.20            | 1.03    |                 |                       |
| 02:11      | HD 8779   | 1         | 1.46            | 0.79    |                 |                       |

Table 3: The Calibrators

| Object   | Class   | $V$  | $v_\odot$ km/s | Ref              |
|----------|---------|------|----------------|------------------|
| Pal 12   | Cluster | 11.99| +27.8          | Harris 1996      |
| HD 203638| K0 III  | 5.77 | +21.9          |                  |
| HD 8779  | gK0     | 6.41 | −5.0           |                  |
| HD 107328| K1 III  | 4.96 | +35.7          | RV calibrator    |
### Table 4: Individual Velocity Results

| Object      | \( v_\odot \) (km/s) | \( rms \) error (km/s) | Comment                                |
|-------------|-----------------------|-------------------------|----------------------------------------|
| HD 203638   | +28.6                 | ±2.5                    | Systematic errors                      |
| HD 8779–1   | −8.9                  | ±3.0                    | due to flexure and slit centering are   |
| HD 8779–2   | +2.7                  | ±2.4                    |                                        |
| HD 8779–3   | +3.7                  | ±2.5                    | typically ± 5–10 km/s                  |
| Pal 12–1    | +26.6                 | ±2.2                    |                                        |
| Pal 12–2    | +26.1                 | ±3.8                    |                                        |
| Pal 12–3    | +28.8                 | ±3.9                    |                                        |
| Pal 12–4    | −24.9                 | ±5.2                    | Probably a non-member                  |
| Phoenix–773 | −8.9                  | ±3.0                    | The most likely                        |
| Phoenix–496 | −22.4                 | ±2.5                    | systemic HI velocity is                |
| Phoenix–845 | −26.8                 | ±3.5                    | \( v_\odot = -23 \) km/s               |
| Phoenix–1058| −3.6                  | ±3.9                    |                                        |
| Phoenix–899 | +8.8                  | ±5.8                    |                                        |
| Phoenix–1274| −31.4                 | ±11.0                   |                                        |
| Phoenix–1328| −9.3                  | ±10.0                   |                                        |

The radial velocity primary reference standard used was based on previous observations of HD 107328 from Tolstoy & Irwin (2000).

The \( rms \) errors were estimated directly from the centroiding of a general Gaussian fit to the primary cross-correlation peak.

Continuum signal:to:noise was typically in the range 5–10 per pixel in the Ca II triplet region.
Fig. 1.— The central 4 arcmin of the Phoenix dwarf galaxy with the adopted slit position marked. North is up and East to the left. This diagram comes from the FIMS observation preparation tool output. The image is a 600sec B-band observation made with FORS1 in August 1999. Marked on the image are the 7 stars identified in our longslit spectrum for which reliable individual spectra could be usefully extracted.

Fig. 2.— Phoenix (R, B−R) Colour-Magnitude Diagram from VLT data taken in August 1999 (Tolstoy et al. 2000). Plotted as star symbols are objects in the slit for which we could extract individual spectra. The labels correspond to those in Figure 1 and also in Table 4.
Fig. 3.— The spectrum of star #1058 (in observed counts) compared with the spectrum of one of the observations of the radial velocity standard HD8779 (scaled down by a factor of 250 and shifted vertically for ease of reference). Also plotted for comparison is a sky spectrum (scaled down by a factor of 40) illustrating the potential problems of residual sky line contamination on the spectrum of the target. A 3-point linear box-car filter was used to smooth the template and target spectra for plotting purposes. The example night sky spectrum is unsmoothed. Despite the brightness of the night sky lines, the extracted target spectrum has a clearly visible Ca II triplet.

Fig. 4.— The normalised cross-correlation of the Phoenix spectrum for star #1058 shown in Figure 3, against a template spectrum constructed from an observation of HD8779. Prior to cross-correlation, both spectra are continuum-corrected and then the template spectrum is set to zero for all regions outside of the ≈10Å zone for each of the CaII absorption lines. No template, flexure or helio-centric corrections have been made for this plot.
