The Absolute Magnitude of RR Lyrae Stars

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Introduction

RR Lyrae stars are one of the standard indicators in the distance scale. Knowing their absolute magnitude, we may determine such basic astronomical parameters as the distance to the Galactic Centre and the distances and ages of the Globular Clusters, which have a cosmological connection with the Hubble constant. They have also been observed in other galaxies of the Local Group where they serve as an important check on other distance indicators, notably Cepheids.

Despite intensive observational efforts over many years, there is still uncertainty in the absolute magnitudes of these stars, and in particular over the variation of the absolute magnitude with chemical composition. RR Lyraes have [Fe/H] in the range from solar to several hundred times deficient, and some work suggests there is no variation of absolute magnitude with [Fe/H] (e.g. the statistical parallax method, Barnes and Hawley, 1986), whilst other work suggests the variation may be as much as one magnitude (Sandage, 1989).

Among the methods used to determine the distance and the absolute magnitude of RR Lyrae stars, the Baade-Wesselink (B-W) method is particularly powerful since it is the only one that uses the intrinsic properties of the star, i.e. luminosity, colour, and radial velocity variations over the pulsation cycle. In its original formulation (Baade, 1926; Wesselink, 1946, 1969) the B-W method uses the light and colour curves of the variable to derive the variation of the angular diameter θ over the pulsation cycle ($\theta \rightarrow \varphi$). The radial velocity curve is used to derive the variation of the linear radius $R \rightarrow \varphi$. From the comparison of the $\theta \rightarrow \varphi$ and $R \rightarrow \varphi$ variations the distance and the absolute magnitude of the star are then derived.

In 1986 two of us (C.C. and G.C.) started at ESO an observing programme aimed at the collection of visual photoelectric photometry and radial velocity data to apply the Baade-Wesselink method to a number of field RR Lyrae stars. In collaboration with Dr. Prévot of the Observatoire de Marseille and Dr. H. Lindgren of ESO, 7 field RR Lyraes have been observed with the 1-m ESO telescope and the 1.5-m Danish telescope equipped with CORAVEL. The data for these stars and the B-W analysis of some of them have been published by Cacciari et al. (1987, 1989a, b) and Clementini et al. (1990).

Recently it has become evident that the use of infrared JHK photometry allows a more accurate application of the B-W method. As shown by Jones et al. (1987), Liu and Janes (1990) and Fernley et al. (1990), the use of the infrared magnitudes and colours (in particular K and V-K) minimizes the discrepancy between photometric and spectroscopic radius determinations on the descending branch of the light curve, which is presumably due to the presence of non-LTE conditions in the pulsating atmosphere. This effect inhibits the application of the B-W method in the visual region over that phase range, but does not significantly affect the infrared region which falls in the Rayleigh-Jeans tail of the energy distribution and is therefore less sensitive to the temperature and its "anomalies".

We have therefore taken JHK observations for three of the previous objects, namely RV Phe, W Tuc and UU Cet, and their absolute magnitudes have been determined using two slightly different formulations of the B-W method, i.e. (a) the Surface-Brightness (SB) method, as described in Cacciari et al. (1989a), and (b) the Infrared Flux (IF) method, as described in Fernley et al. (1990). These are at present the two most accurate and widely used techniques to derive $M_V(RR)$, and both are capable of determining the absolute magnitude with an error of $\pm$ 0.15–0.20 mag. Although this degree of accuracy is not sufficient to resolve some of the important questions related to the variation in absolute mag-

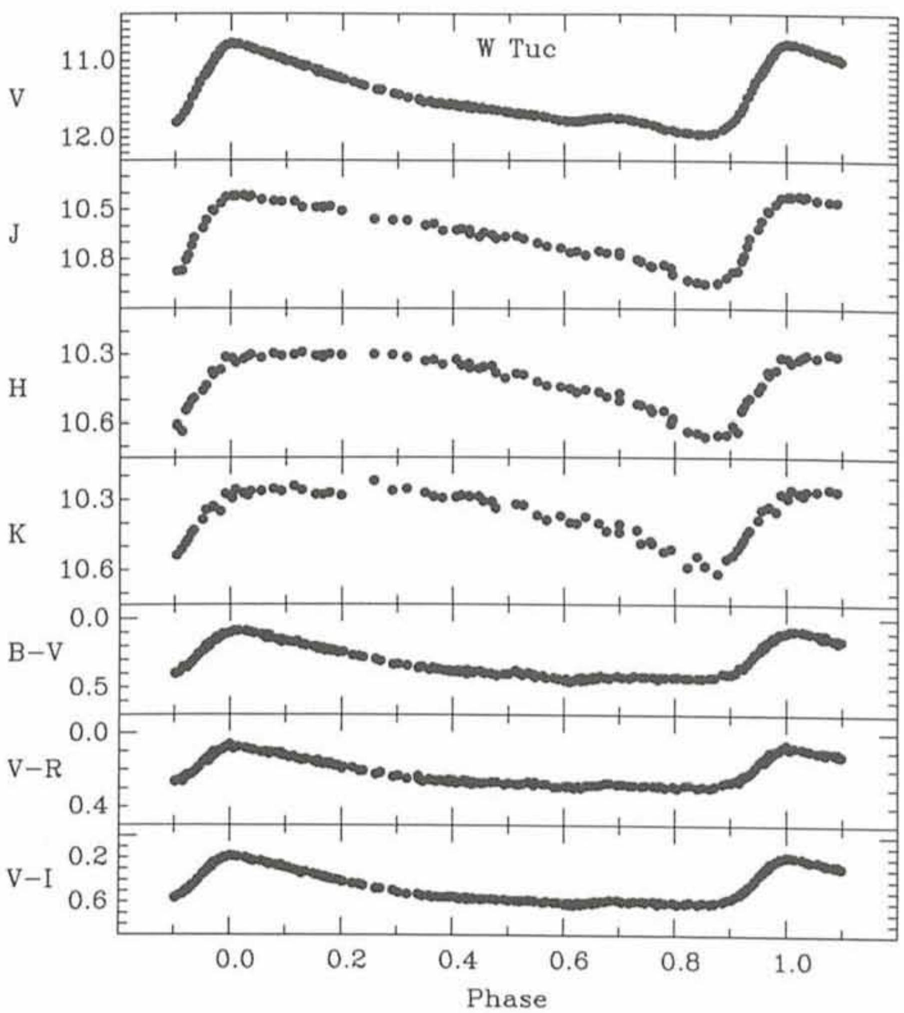

Figure 1: *Light (V, J, H, and K) and colour (B−V, V−R, and V−I) curves for W Tuc.*

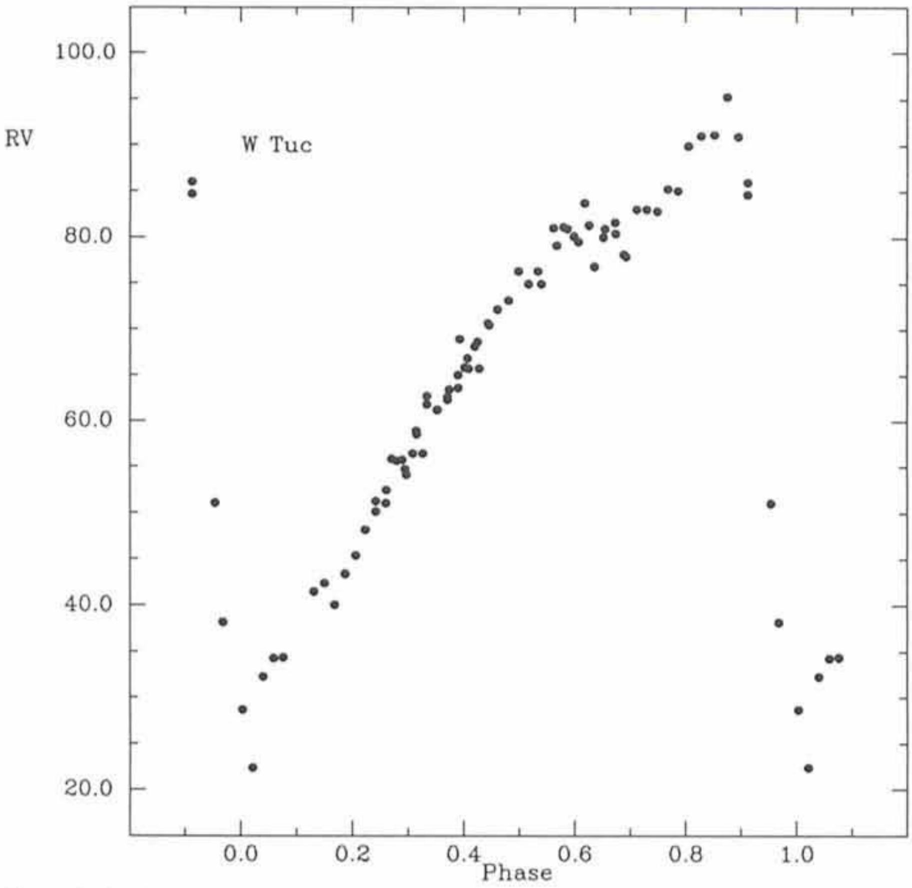

Figure 2: *Radial velocity curve for W Tuc.*

nitude of RR Lyrae stars with period and metallicity (such as the age of globular clusters with a smaller uncertainty than the current 2–3 Gyrs), it can be substantially improved by enlarging the statistics, i.e. applying the methods to as many stars as possible (see Sandage, 1989, 1990 and Sandage and Cacciari, 1990, for a review and detailed discussion of this and related problems).

The Observations

Both SB and IF methods require very accurate photometric (BVRIJHK) and radial velocity data as input parameters, the knowledge of reddening and metallicity of the star, and a model atmosphere for the proper metallicity and gravity. The infrared light curves for the three stars were collected between October 19 and 28, 1990 using the 1.0-m telescope at the European Southern Observatory, La Silla, Chile (Cacciari et al., 1991). The BVRI photoelectric photometry and the radial velocities of the three stars had been obtained in previous observing runs at La Silla (Cacciari et al., 1987, 1989b, and Clementini et al., 1990). The visual photometry is on the Johnson-Cousins photometric system. The Walraven photometry used in the IF method is by Lub (1977). The radial velocities were obtained with the CORAVEL photoelectric scanner (Baranne et al. 1977, 1979; Mayor, 1985). The accuracy of the CORAVEL radial velocities of an RR Lyrae star depends on the metallicity, the average colour of the star, and the phase at which v_r is measured, the correlation dip being shallower and less well defined when the star has earlier spectral type. Typical accuracies for individual data points are ±1–2 km/sec for the radial velocity data, and ±0.01–0.02 mag for magnitudes and colours. The photometric and radial velocity data for one of the stars, namely W Tuc, are shown in Figures 1 and 2 as an example.

Analysis and Results

For the three programme stars, RV Phe, W Tuc and UU Cet, we have adopted respectively [Fe/H] = −1.5, −1.35, and −0.90, and E(B−V)=0.015, 0.005 and 0.025. We have then applied the IF and SB methods as described in detail in Fernley et al. (1990) and Cacciari et al. (1989a) respectively, avoiding the phase interval around maximum light since the stellar atmospheres are presumably in non-LTE and static model atmospheres are therefore not adequate to describe their characteristics in that interval of phase. During the ascending branch of the light curve there is considerable evidence for a shock wave in the upper atmosphere of RR Lyrae stars, as indicated by emission in the Balmer lines and an ultraviolet (U-B) excess (Preston and Paczynski, 1964). This is clearly shown in Figure 3 where we report three orders from the CASPEC echelle spectrum of an RR Lyrae star in the globular cluster M4 that one of us (G.C.) had obtained in a previous observing run at La Silla. The spectrum corresponds to φ=0.96, i.e just before the star reaches the maximum light. The presence of these emissions is generally interpreted as due to shock waves caused by the pulsation being "out of phase" in the higher layers of the atmosphere. As material from the new pulsation cycle drives outwards it collides with material falling in from the old pul-

Table 1: *Summary of results. The two values in the SB method are from optical colours (left) and (V−K) colours (right).*

	IF			SB		
	UUCet	RVPhe	WTuc	UUCet	RVPhe	WTuc
$<R/R_\odot>$	5.55	4.92	5.78	5.20 – 5.54	5.32 – 4.60	5.68 – 5.55
$<T_e>$	6308	6293	6395	6363 – 6293	6370 – 6292	6517 – 6441
d(pcs)	1826	1525	1529	1782 – 1821	1650 – 1386	1529 – 1452
$<M_v>$	0.697	0.954	0.521	0.75 – 0.70	0.77 – 1.16	0.52 – 0.63
$<M_k>$	− 0.466	− 0.200	− 0.570	–	–	–
$<\log L/L_\odot>$	1.639	1.530	1.698	1.598 – 1.633	1.619 – 1.472	1.716 – 1.675
$<M/M_\odot>$	0.64	0.49	0.65	0.54 – 0.64	0.60 – 0.41	0.62 – 0.58

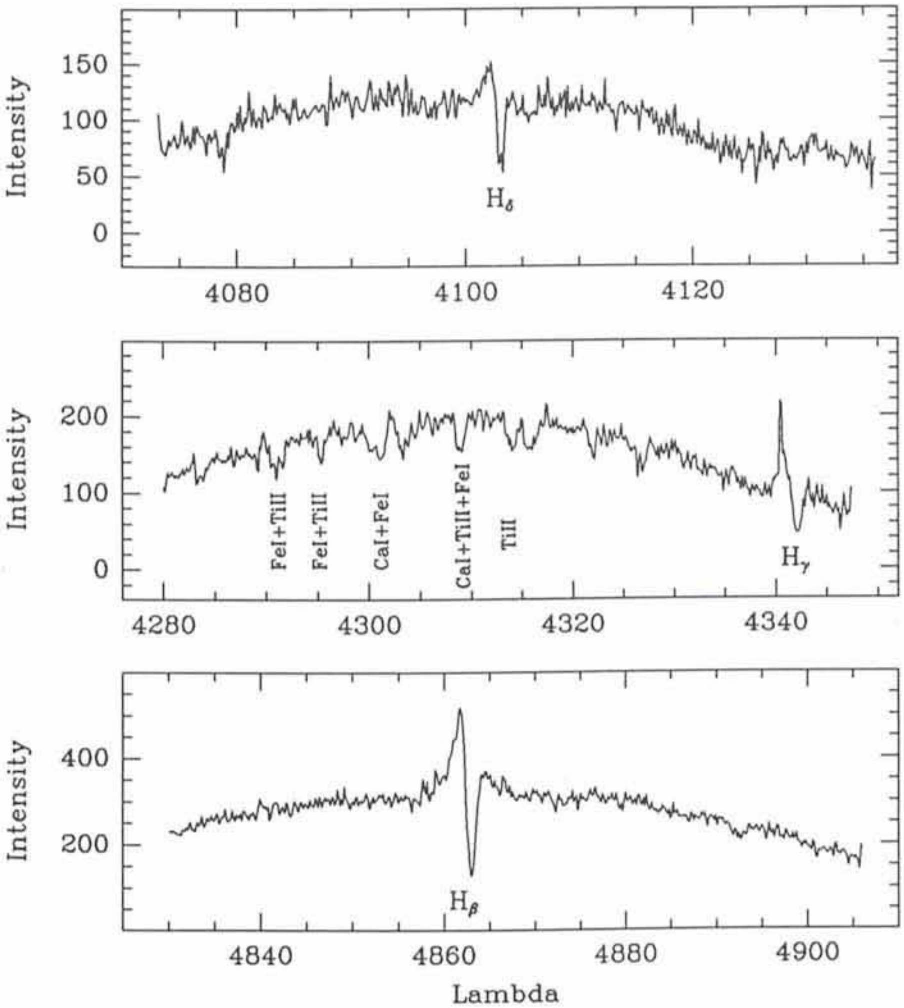

Figure 3: *Three orders from a CASPEC spectrum of variable V29 in the globular cluster M4. The spectrum corresponds to $\varphi \sim 0.96$ of the pulsation cycle of the star.*

sation cycle. The resulting collisions produce both the Balmer line emission and the (U-B) excess. Figure 3 shows that some emission occurs in weak metal lines as well.

To avoid these problems, the IF method has been applied over the phase interval $\Delta\varphi$=0.05–0.85, the SB method plus V–K colours has been applied over the phase interval $\Delta\varphi$~0.10–0.80, and the SB method plus visual colours (i.e. V–R and V–I) has been applied on an even more restricted phase range (varying from star to star) to avoid additional distortions in the flux distribution that do not normally occur in the infrared range. The $\theta \rightarrow \varphi$ and $R \rightarrow \varphi$ fits for W Tuc are shown in Figure 4 as an example. The angular diameters θ have been derived using as temperature indicators the V–R, V–I and V–K colours respectively in the SB analysis, while the entire spectral range from ultraviolet to infrared has been used in the IF analysis. The results obtained for the three stars are summarized in Table 1, where the output parameters from visual and V–K colours in the SB method are shown separately, and one can see that the two methods are rather consistent, in particular when the (V–K) colour is used in the SB method.

The present types of analysis have been previously applied to a number of field RR Lyrae stars by many authors. The most recent compilations are given by Cacciari et al. (1991) and Jones et al. (1991), and include 24 stars that have been analysed using infrared data. We refer to these papers for more details and references. From these data one derives a relation between the absolute magnitude of the RR Lyrae stars M_V(RR) and the metallicity (see Fig. 5):

$$M_V(RR)=0.19[Fe/H]+1.01$$

(Cacciari et al., 1991). The slope of this relation is however still somewhat controversial, as Jones et al. (1991) found

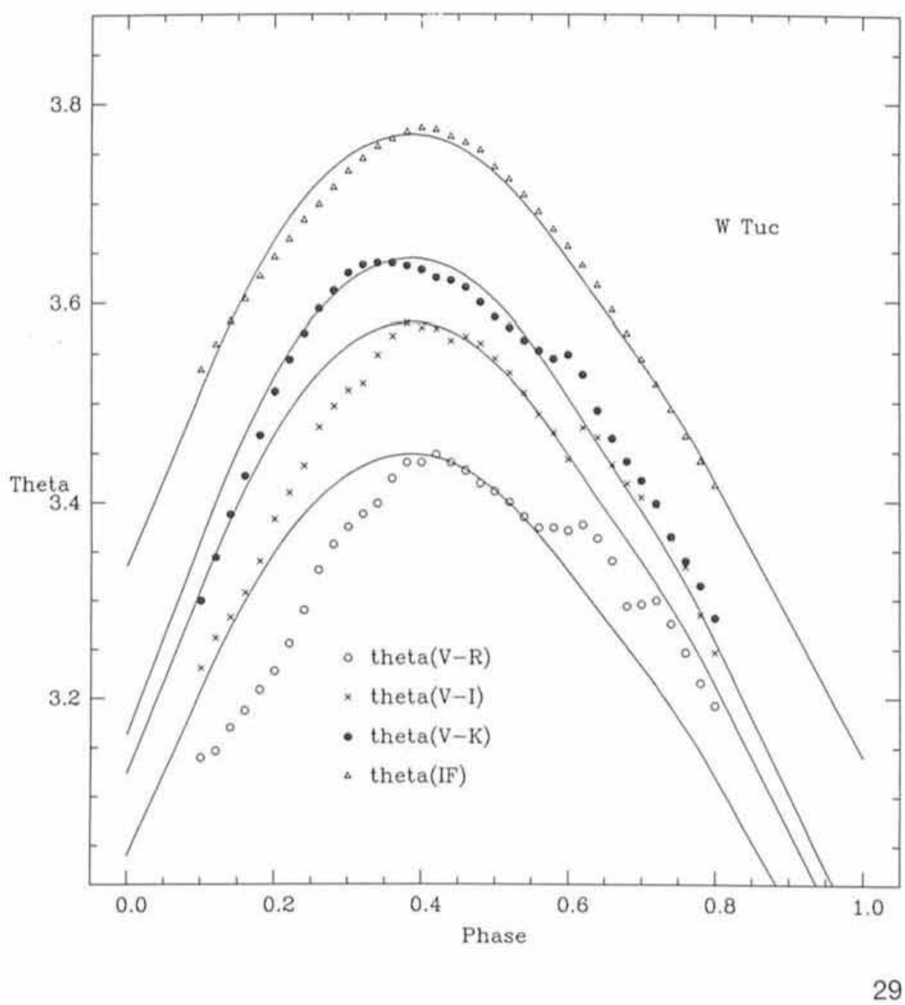

Figure 4: *Angular diameters θ vs. phase for W Tuc as derived from V magnitudes and (V–R) (○), (V–I) (×) and (V–K) (●) colours with the SB method, and from the IF method (Δ). The solid lines represent the radial displacements ΔR derived from spectroscopy, corresponding to M_V=0.28, 0.52, 0.63 and 0.52 respectively.*

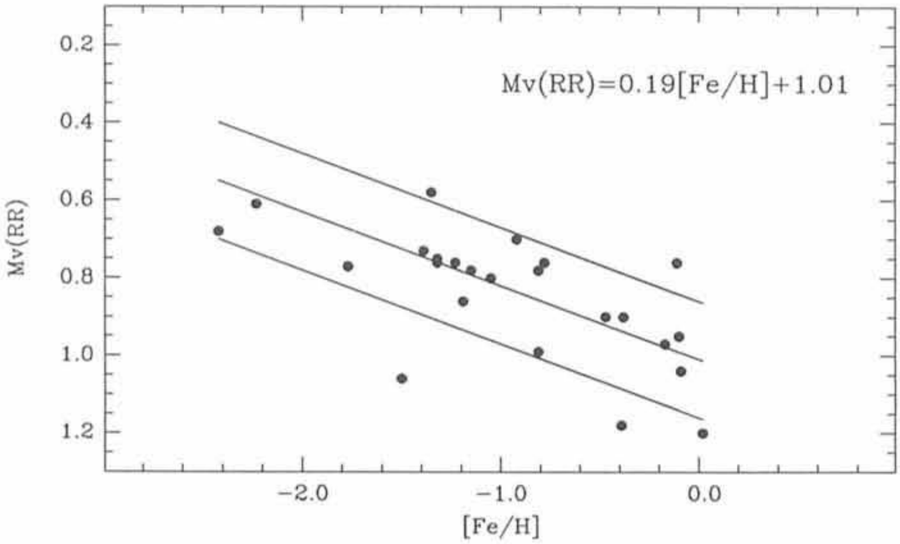

Figure 5: *Summary of the RR Lyrae absolute magnitude determinations obtained from infrared data (IF method, or SB plus V−K colours). The solid lines define the range $\Delta M_V = \pm 0.15$ mag around the ridge line defined in the text.*

~0.16 using slightly different values of M_V(RR) for a few very metal-poor and very metal-rich stars, and values ranging from 0.20 to 0.38 have been found with a number of methods and assumptions, as reviewed and discussed by Buonanno et al. (1990).

The use of the above relationship to estimate globular cluster ages leads to 16 and 19 Gyrs for metal-rich and metal-poor clusters respectively on the assumption that [CNO/Fe]=solar, and to slightly lower values depending on the amount and degree of metallicity dependence of O enhancement, if any.

The obvious further step with respect to the work done so far on field stars is to extend this type of analysis to globular cluster RR Lyraes. Since in a given cluster RR Lyraes are all at the same distance and have the same metal abundance (with the exception of ω Cen), the study of a sufficiently large number of them can provide a more accurate determination of the average absolute magnitude in each cluster and of its dependence on metallicity. Globular cluster variables are however much fainter than their field counterparts, and the observations are correspondingly more difficult and time-consuming. In particular CORAVEL, in its present configuration, cannot be used for RR Lyraes fainter than V=12.5−13 mag, while the brightest RR Lyraes in globular clusters at minimum light are V≥13.5. For this reason very few results have appeared on this topic (Cohen and Gordon, 1987, Liu and Janes, 1990), although considerable effort is being devoted to it. We have started a programme on the RR Lyrae variables in M4, and have collected BVRIJHK photometry and CASPEC high-resolution spectra for 4 variables, covering the entire pulsation cycles. The data are presently being analysed and will be the subject of a forthcoming paper.

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Galaxy Photometry with SEST: How Big Are Galaxies at Millimetric Wavelengths?

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Introduction

The information currently available on the electromagnetic emission of normal galaxies at long wavelengths (λ = 100 ÷ 3000 μm) is still quite sparse and serious discrepancies are found among different observations. Only very recently the improvement in instrument sensitivity has allowed exploration of the galaxy submm-mm continuum. Data on millimetre continuum emission of galaxies are mainly confined to active galaxies (both AGNs and starburst galaxies), because of their enhanced nuclear emission, while only a handful of normal spirals have been observed so far at these wavelengths (Chini et al., 1986, Stark et al., 1988; Eales et al., 1989).