The redshift of the gravitationally lensed radio source PKS 1830−211[1]

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ABSTRACT

We report on the spectroscopic identification and the long awaited redshift measurement of the heavily obscured, gravitationally lensed radio source PKS 1830-211, which was first observed as a radio Einstein ring. The NE component of the doubly imaged core is identified, in our infrared spectrum covering the wavelength range 1.5-2.5 μm, as an impressively reddened quasar at $z = 2.507 \pm 0.002$. The mass contained within the Einstein ring radius is $M(r < 2.1h^{-1}Kpc) = 6.3 \times 10^{10}h^{-1}M_\odot$ for $\Omega_M = 1$ or $M(r < 2.4h^{-1}Kpc) = 7.4 \times 10^{10}h^{-1}M_\odot$ for $\Omega_M = 0.3$. Our redshift measurement, together with the recently measured time delay (Lovell et al. 1998), means that we are a step closer to determining H_0 from this lens. Converting the time delay into H_0 by using existing models leads to high values of the Hubble parameter, H_0=65^{+15}_{-9} for $\Omega_M = 1$ and H_0=76^{+18}_{-10} for $\Omega_M = 0.3$. Since the lensing galaxy lies very close to the center of the lensed ring, improving the error bars on H_0 will require not only a more precise time delay measurement, but also very precise astrometry of the whole system.

Subject headings: cosmology: observations - gravitational lensing - infrared

Subject headings: quasars: individual (PKS 1830-211)

[1]Based on observations collected at the European Southern Observatory, La Silla, Chile (ESO Program 61.B-0413)

1. Introduction

The compact, flat-spectrum radio source PKS 1830-211 (Subrahmanyan et al. 1990, Jauncey et al. 1991) is a well studied gravitational lens located behind the galactic plane $(l, b) = (12, -5)$. At radio wavelengths, PKS 1830-211 consists of two bright, flat-spectrum sources embedded in a ring like structure with a diameter of $1''$. The radio emission is known to be variable, and a time delay of 26 days has been determined by monitoring the source at 8.6 Ghz (Lovell et al. 1998). At millimeter wavelengths, molecular absorption lines are detected in both sources (Wiklind & Combes 1996, Wiklind & Combes 1998, Frye, Welch & Broadhurst 1997), and are attributed to a galaxy at $z = 0.886$. Additionally, redshifted 21cm absorption is found at $z = 0.193$ (Lovell et al. 1996). The relative role of these two systems in lensing of the radio source is unclear (Lovell et al. 1997).

The optical identification of PKS 1830-211 has long been hampered by the presence of a nearby, bright M-star (Djorgovski et al. 1992) and by obscuration by both the galactic plane and the lens itself. PKS 1830-211 was finally identified in deconvolved images taken at infrared wavelengths (Courbin et al. 1998). These images show the NE component of the source, the M-star and the SW component of the source, most likely blended with the lensing galaxy. The source is very red: the NE component has $I - K \approx 7$, so that at K (2.15 μm) it is much brighter than the nearby M-star, which dominates at optical wavelengths.

In this letter, we describe how we were able to determine the redshift of PKS 1830-211 from infrared spectroscopy carried out with SOFI, the new IR imager and spectrograph on the ESO New Technology Telescope (NTT) at La Silla, Chile (Moorwood, Cuby & Lidman 1998). The data also allow us to derive the extinction along the line of sight to PKS 1830-211 and an estimate of the mass of the lensing galaxy at z=0.886.

2. Observations and Reductions

PKS 1830-211 was observed with SOFI (SOFI stands for Son OF ISAAC, the latter is the near-IR instrument on UT1 of the Very Large Telescope at Paranal, Chile) during the night of June 13, 1998. SOFI is an IR instrument capable of imaging, polarimetry, and low resolution spectroscopy. The detector is a Hawaii 1024$\times$1024 HgCdTe array. Spectra were taken with the red grism, which covers the wavelength range from 1.51 to 2.54 μm, and with the $1''$ slit, which gives a resolution of 700 at 2.1 μm. The slit was aligned to pass through both the NE and SW components of source (see Figure 1.).

For accurate sky subtraction, the source was alternatively observed at two positions separated by 40 arcseconds along the slit. At each position, the exposure was 180 seconds. The conditions at the time of the observation were very cloudy, so only 24 minutes of useful data were obtained.

The night sky, which consists of bright emission lines and a thermal continuum, is effectively removed by subtracting, from each other, frames taken at alternative positions along the slit. The resulting images are then flat-fielded, registered, and combined to give a two dimensional spectrum. The spectrum of the source is then extracted and wavelength calibrated, which is done by fitting arc lines from a Xenon lamp in the adaptor. The residuals of the fit are 0.5 Å. The extracted spectrum is then divided by that of a very hot star, in this case an O6 star, to remove the strong atmospheric absorption features that appear in infrared spectra. In a final step, the spectrum is multiplied with a blackbody curve that is appropriate for an O6 star. We have used a blackbody with a temperature of 36,000 K. At this temperature and wavelength, the shape of the blackbody curve is not a sensitive function of the temperature. Note that the O6 star may contain weak Bracket and HeI lines that are introduced in the reduction process. However, there is no evidence of them in the fully reduced spectrum.

3. Results

Figure 2 displays the reduced spectrum of PKS 1830-211. Regions of significant atmospheric absorption are marked by horizontal lines. Since the atmosphere is almost totally opaque near 1.9 μm and beyond 2.5μm, the data in these regions have been deleted. Due to the presence of clouds during the observations, no absolute flux calibration could be carried out and the spectrum in Fig. 2 is shown on a relative F_λ flux scale. We could not use the K-band flux derived by Courbin et al. (1998) to put the spectrum on an absolute flux scale as the source is variable in the IR. The spectrum contains a contribution from the M-star (see Figure 1) which lies $0\farcs5$ to the North of the NE component of the QSO. At 1.25 μm the M-star is twice as bright as the NE component. At 2.15 μm the NE component is 3 times brighter that the M-star (see Courbin et al. 1998) and largely dominates the total flux that falls within the slit.

A very strong Hα emission line is seen at a redshift of $z = 2.507 \pm 0.002$. The dominant source of uncertainty in the redshift is due to internal instrumental flexure. Also visible, but at lower signal to noise ratios, are Hβ and possibly the 4959 Å and 5007 Å lines of [OIII]. All four lines are marked in Fig. 2. The rest equivalent width of the Hα line is 170 Å and the velocity width is 2600 $\mathrm{km\,s^{-1}}$. Both measures are somewhat lower than the average value for high redshift quasars (Espey et al. 1989), although the range for high redshift quasars are large. The Hα line cannot be fitted with a single Gaussian. There are broad wings on either side of the line, particularly on the red side.

The region around the Hβ and [OIII] lines is quite noisy. The lines may be blended with a FeII multiplet, #42 in Oke & Lauer (1979). This multiplet is a common feature in quasar spectra at both low and high redshifts. However, the strength of this feature varies greatly from one quasar to the next (Boroson & Green 1992; Hill, Thompson & Elston 1993; Murayama et al. 1998). A spectrum with better signal to noise is required before these features can be positively identified. The region near 18,000 Å is on the edge of the strong absorption feature that lies between the H and K IR windows.

The redshift determined from Hβ line alone is $z = 2.507$, the same as that determined from Hα. Thus, despite the noisy nature of the region surrounding this line, it is unlikely that the line at 23,000 Å has been misidentified as Hα.

The 5007 Å [OIII] line is slightly blueshifted ($z = 2.504$) with respect to the Hα and Hβ lines. If the relative motion of the broad and narrow line regions is along the line of site, the difference in the redshift corresponds to a velocity shift of 250 km/s. This has been observed in other quasars (Nishihara et al. 1998). Other common quasar emission lines such as HeII at 4686 Å, HeI at 5876 Å, Hγ, [OIII] at 4363 Å and a FeII complex around 4500 Å are not detected, although they are within the wavelength limits of our spectrum in Figure 2. However, given the strength of the Hβ line, this is not surprising.

The continuum shows a steep increase towards longer wavelengths. Between 1.6 and 2.2 μm it can be approximated by a power law $F_\nu \propto \nu^\alpha$ with a spectral index $\alpha \approx -4$. This is considerably steeper than the median value of $\alpha \approx -0.3$ for quasar spectra (Francis et al. 1991), even considering orientation effects (Baker & Hunstead, 1995), and it implies a considerable amount of reddening. Any reddening in the O star that was used to remove the atmospheric absorption features would bias the derived reddening in PKS 1830 to smaller and not higher values.

4. Extinction

By comparing the radio and near-IR flux ratios between the lensed components of PKS 1830-211, Courbin et al. (1998) estimated a differential extinction in the rest frame of the lens of $E(B-V) = 2.75$ between the SW and NE components. This value is estimated from K band observations and assumes that the lensing galaxy does not contribute to the flux of the SW source (Courbin et al. 1998). At the lens redshift, the K band is still in the near-IR, so we can safely assume that extinction does not depend dramatically on galaxy type, as it could at shorter wavelengths. Thus, if we adopt a galactic extinction law with $R_V = 3.05$, we find that the SW component is absorbed by $A_V = 8.6$ magnitudes relative the NE component.

Our near-IR spectrum is dominated by the light from the NE component (the SW component is 3 magnitudes fainter), and offers the opportunity to estimate the line-of-sight absolute extinction. For this purpose, we do not use the slope of the continuum, which is partially contaminated by the nearby M-star, but instead measure the Balmer decrement, given by the line flux ratio $F[\mathrm{H}_\alpha]/\mathrm{F}[\mathrm{H}_\beta]$, and compare it with previous measurements of other quasars. Common measurements give $F[\mathrm{H}_\alpha]/\mathrm{F}[\mathrm{H}_\beta] \sim 4-5$ and are interpreted in terms of moderate intrinsic reddening (e.g., Hill, Thompson & Elston 1993) or enhanced Hα emission due to collisional excitation (Baker et al. 1994). Baker & Hunstead (1995) show that the Balmer decrement depends on the core-to-lobe flux ratio, R. They find $F[\mathrm{H}_\alpha]/\mathrm{F}[\mathrm{H}_\beta]$ in the range 5-6 for $R > 1$, and up to 10 for $R < 0.1$.

If we assume that the Hβ line is uncontaminated by other lines, $F[\mathrm{H}_\alpha]/\mathrm{F}[\mathrm{H}_\beta] = 11 \pm 2$. This implies that PKS 1830-211 is significantly reddened. If we assume further that all the absorption occurs in the z=0.886 lens, that the Balmer decrement of the unreddened quasar is five, and that a galactic absorption law is applicable, we find that the NE component has $E(B-V) \approx 1.2$ in the rest frame of the lens. Thus, the extinction towards the NE component in the rest frame of the lens is $A_V \approx 3.7$ magnitudes, which implies an extinction of $A_V \approx 12$ magnitudes towards the SW component.

We stress that these estimates are very uncertain. They can change if any of the following are true: (i) some fraction of the reddening is caused by our galaxy or by the H1 absorber at $z = 0.19$, (ii) the Hβ line flux is overestimated, (iii) PKS 1830-211 is reddened at the source, (iv) the SW component contributes significantly to the flux, (v) the SW component is blended with some other object, for example, the lensing galaxy (Courbin et al. 1998). (vi) the galactic extinction law does not apply for the lens galaxy, and (vii) the Balmer decrement of the unreddened quasar is not five.

5. Discussion-Conclusions

With the source and lens redshifts known, the mass interior to the radio ring can be estimated from a simple point mass model. Table 1 gives this mass for two different cosmologies. Such relatively low masses, in the range $6 - 14 \times 10^{10} M_{\odot}$, combined with the fact that a very significant amount of dust is present in the deflector, suggests that the deflector is a late type spiral. More detailed models (Nair, Narasimha & Rao 1993), which incorporate some constraints on the position of the lensing galaxy relative to the QSO images and on the geometry of the source, give even lower values: $2.5 - 5 \times 10^{10} M_{\odot}$. The models of Kochanek & Narayan (1992), which use the radio structure of the lens to characterise the lensing potential, give one dimensional velocity dispersions that range between 150 and 210 km/s.

PKS 1830-211 is known to be variable at radio and millimeter wavelengths (van Ommen et al. 1995, Combes & Wiklind 1998, Lovell et al. 1998). With the present measurement of the redshift of the source, this quasar becomes a good candidate for constraining H_0. Recently, a time delay of 26^{+4}_{-5} days between its two point-like components was reported (Lovell et al. 1998). This is substantially smaller than the time delay of 44 ± 9 days reported by van Ommen et al. (1995). Since the lower estimate of the time delay was obtained from radio observations with high angular resolution, almost allowing for the separation of the NE and SW components, we consider it to be more accurate. We use this low value with the models of Nair, Narasimha & Rao 1993 to deduce H_0. The derived estimates tend to be higher that those derived from other lensed quasars, even with a large Ω_M. For $\Omega_M = 1$, H_0=65^{+15}_{-9}; for $\Omega_M = 0.3$ it increases to H_0=76^{+18}_{-10}.

The rather large uncertainty in the time delay, approximately 20%, translates directly into an uncertainty in H_0. This uncertainty may be improved by monitoring PKS 1830-211 in the near-IR. In particular, K-band observations, where the source is bright due to the presence of redshifted Hα emission (see Fig. 2), should allow accurate photometry of both the NE and SW components.

Our IR observations of the quasar obtained in March and June 1998 show that the NE and SW components have brightened by $0.^m35$ and $0.^m25$ respectively. Similar changes were also found at millimeter wavelengths during the same epochs (Wiklind, 1998).

The strong Hα line can be used to search for differences between continuum and line variability and thus help to distinguish between intrinsic source variability and differential magnification of the continuum versus the broad-line region due to the passage of compact micro-lensing sources in the lensing galaxy. Monitoring of PKS 1830-211 carried out simultaneously in H (continuum) and K (Hα) would provide adequate material, not only for the measurement of H_0, but also for the study of micro-lensing itself.

Newly available NICMOS images show that the lensing galaxy is located near to the center of the radio ring, so that the two QSO images probe the lensing potential at similar distances from the lens center. We can therefore expect that detailed modelling of the system will strongly depend on the accuracy reached on the position of the lensing galaxy, as found in PG 1115+080 (e.g., Keeton & Kochanek, 1997, Courbin et al. 1997, Impey et al. 1998).

The relative ease with which we obtained the redshift of this lensed radio source by IR spectroscopy lends considerable hope to the identification of the other classical radio lenses for which source redshifts are still outstanding.

The authors would like to thank D. Hutsemékers for useful conversations on reddening by the lensing galaxy. F.C. is supported by contracts ARC 94/99-178 “Action de Recherche Concertée de la Communauté Française” and Pôle d’Attraction Interuniversitaire P4/05 (SSTC, Belgium).

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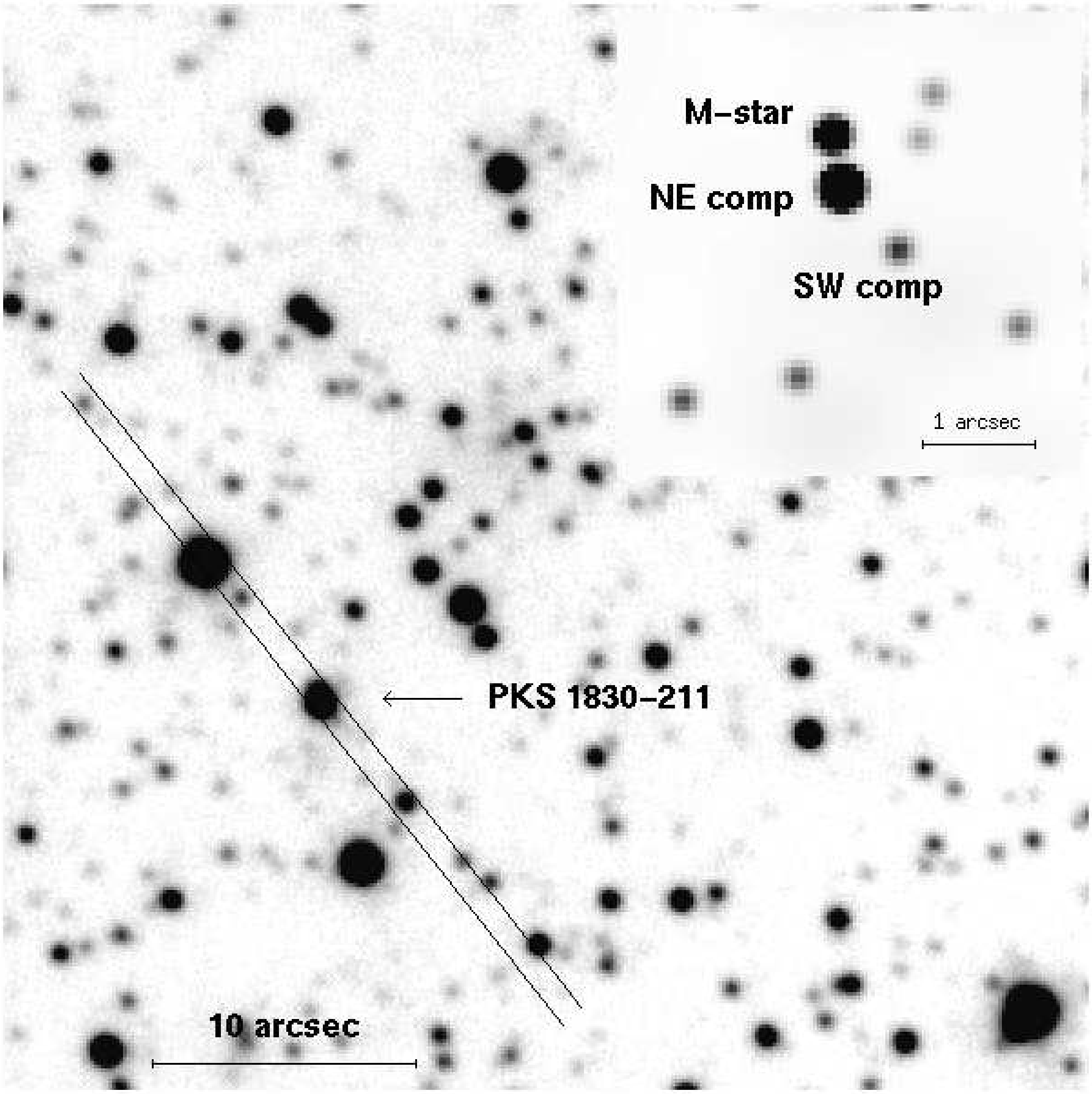
Table 1: Mass interior to the Einstein ring in PKS 1830-211 for different cosmologies.

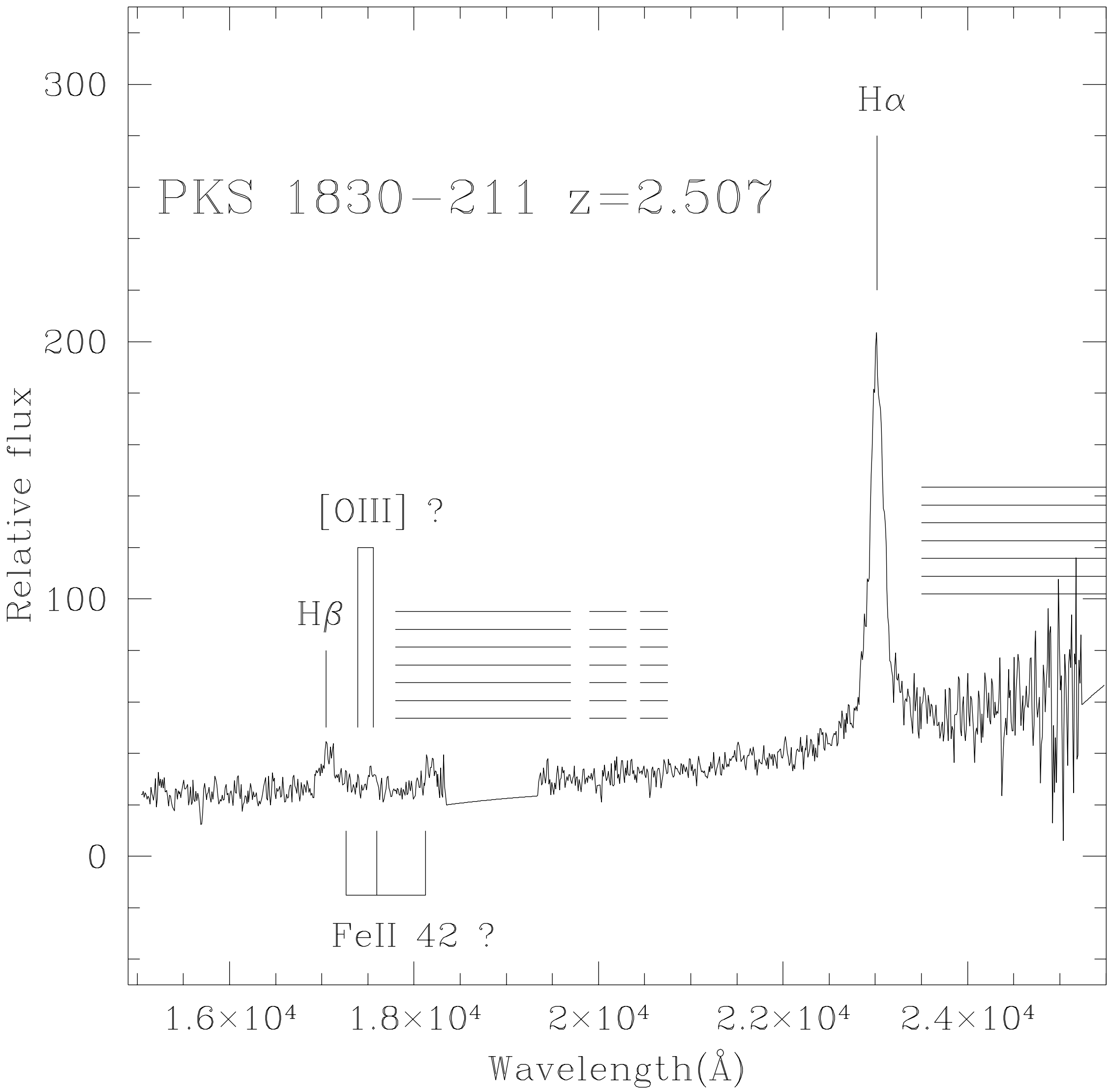
	$D_l D_s / D_{ls}$ (Gpc)	r_E (Kpc)	Mass $(10^{10} M_{\odot})$
$H_0 = 50, \Omega_M = 1$	4.2	4.1	12.5
$H_0 = 50, \Omega_M = 0.3$	4.8	4.7	14.0
$H_0 = 100, \Omega_M = 1$	2.1	2.1	6.3
$H_0 = 100, \Omega_M = 0.3$	2.5	2.3	7.4

Note. — The adopted Einstein radius of the radio ring is the one obtained from the millimeter observations by Frye et al. (1998), i.e., r_E=0.49$''$. D_l and D_s denote the angular diameter distances to the lens and source. D_{ls} is the angular diameter distance between the lens and the source.

Fig. 1.— Part of an Ks image of PKS 1830-211 taken with SOFI at the NTT, with the position of the slit displayed. The seeing is $0\farcs6$. North is up and East left. The inset shows the deconvolved central region surrounding PKS 1830-211. The M-star and the NE and SW components of PKS 1830-211 are readily apparent in the deconvolved image, which has a resolution of $0\farcs2$.

Fig. 2.— Spectrum of PKS 1830-211. The spectrum is plotted on a relative flux scale against observed wavelength. Regions of strong atmospheric absorption are marked with horizontal lines. Regions that are almost opaque are excluded.


M–star
NE comp
SW comp
1 arcsec
PKS 1830–211
10 arcsec


PKS 1830−211 z=2.507
Hα
Hβ
[OIII] ?
FeII 42 ?
Relative flux
Wavelength(Å)
300
200
100
0
1.6×10⁴
1.8×10⁴
2×10⁴
2.2×10⁴
2.4×10⁴