The Double-Lined Spectroscopic Binary θ^1 Ori E: An Intermediate-Mass, Pre-Main-Sequence System

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INTRODUCTION

Θ^1 Ori E = ADS 4186 E = P 1864 = NSV 2291 is the fifth brightest (but poorly known) star in the optical visual and the second brightest X-Ray source in the Orion Trapezium.

Published data include:

Optical and IR Photometry:

Photo-visual magnitude = 11.4	(Parenago 1954)
Variable? (amplitude 0.41 mag)	(NVS: Kukarkin 1982)
U=9.2 B=10.10 V= 9.91 R=9.01 I=8.54	(Bondar *et al*. 2000)
V=10.31:	(HST: Prosser *et al*. 1994)
I=8.40	(Hillenbrand 1997)
K'=6.77	(McCaughrean & Stauffer 1994)
H=7.81 K=6.90	(Hillenbrand *et al*. 1998)
J=7.55 H=7.14 K=6.90	(Muench *et al*. 2002)

INTRODUCTION

Spectral Type:

- G + B5-8 (Herbig 1950, Parenago 1954)
- G0-5 + B5-8 (Kukarkin *et al.* 1982)
- F8Vn (Abt, H., as cited by Ku *et al*. 1982)
- G4-K3 (Luhman *et al*. 2000, from near-IR spectra)

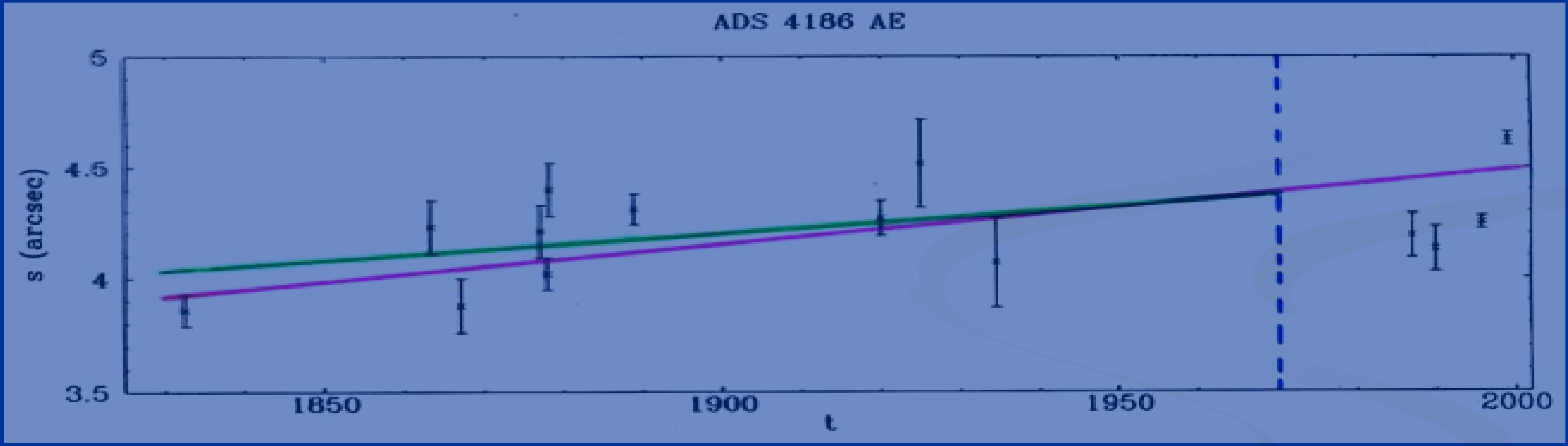
Radio and X-ray observations:

- Variable, non-thermal radio source (Felli et al. 1993)
- Second brightest X-ray source, variable in timescales > 10^3 sec (Ku *et al*. 1982, Feigelson *et al*. 2002)

INTRODUCTION

Dynamics:

The tangential motion of Θ^1 Ori E, relative to Θ^1 Ori A, suggests the former is escaping from the Trapezium (Allen et al 1974, 2004).



No radial velocity information was available for the star and its spectral type was very uncertain, so we proceeded to obtained high-resolution spectra of the object.

OBSERVATIONS

Echelle spectra (R~20000) were obtained with the 2.1m telescope at the National Astronomical Observatory in San Pedro Mártir, Baja California, México:

2004 Oct.	4 nights,	5 spectra
2004 Dec.	4 nights,	9 spectra
2006 Jan.	10 nights,	72 spectra
2006 Feb.	1 night,	2 spectra
2006 Mar.	2 nights,	6 spectra

Based on the January spectra, Costero et al. (2006) reported their finding that Θ^1 Ori E is a pre-main-sequence double-lined spectroscopic binary, with period around 10.5 days. Two months later, G. H. Herbig privately communicated us that he and R. F. Griffin had independently discovered the binary nature of the object.

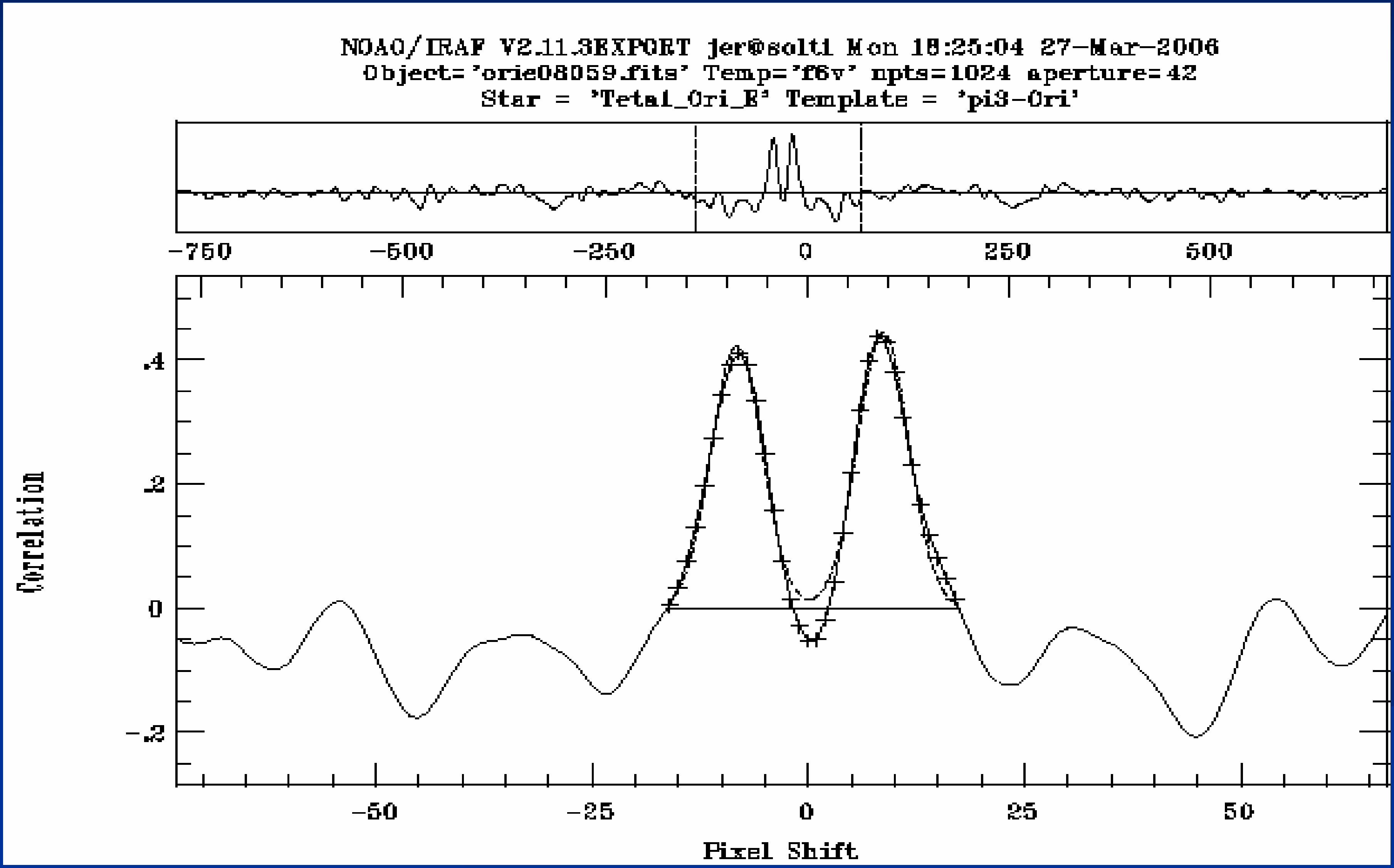
ORBITAL PARAMETERS

We cross-correlated 61 spectra of θ^1 Ori E –in which the line systems of both components are resolved– with the spectra of two standard stars chosen to have well-measured radial velocities and low $v \cdot sin \cdot i$, namely π^3 Ori (F6V) and β Vir (F9V). Next slide shows an example of the correlation function.

Three contiguous Echelle orders were used, spanning from 5120 to 5515 Å. In that spectral range:

- The spectral efficiency of the instrument is high
- There are few and relatively weak nebular or telluric lines
- Several strong and mid-intensity stellar lines are present
- The contamination from the nearby θ^1 Ori A is smaller.

Example of correlation function



θ^1 Orionis E *ORBITAL PARAMETERS*

The resulting bimodal correlation functions yielded heliocentric radial velocities for both binary components, from which we have computed orbital parameters. Since we find that the eccentricity is very small (< 0.001), the solution was forced to be that of a circular orbit.

Period = 9.896 ± 0.003 days

e = 0 (forced)

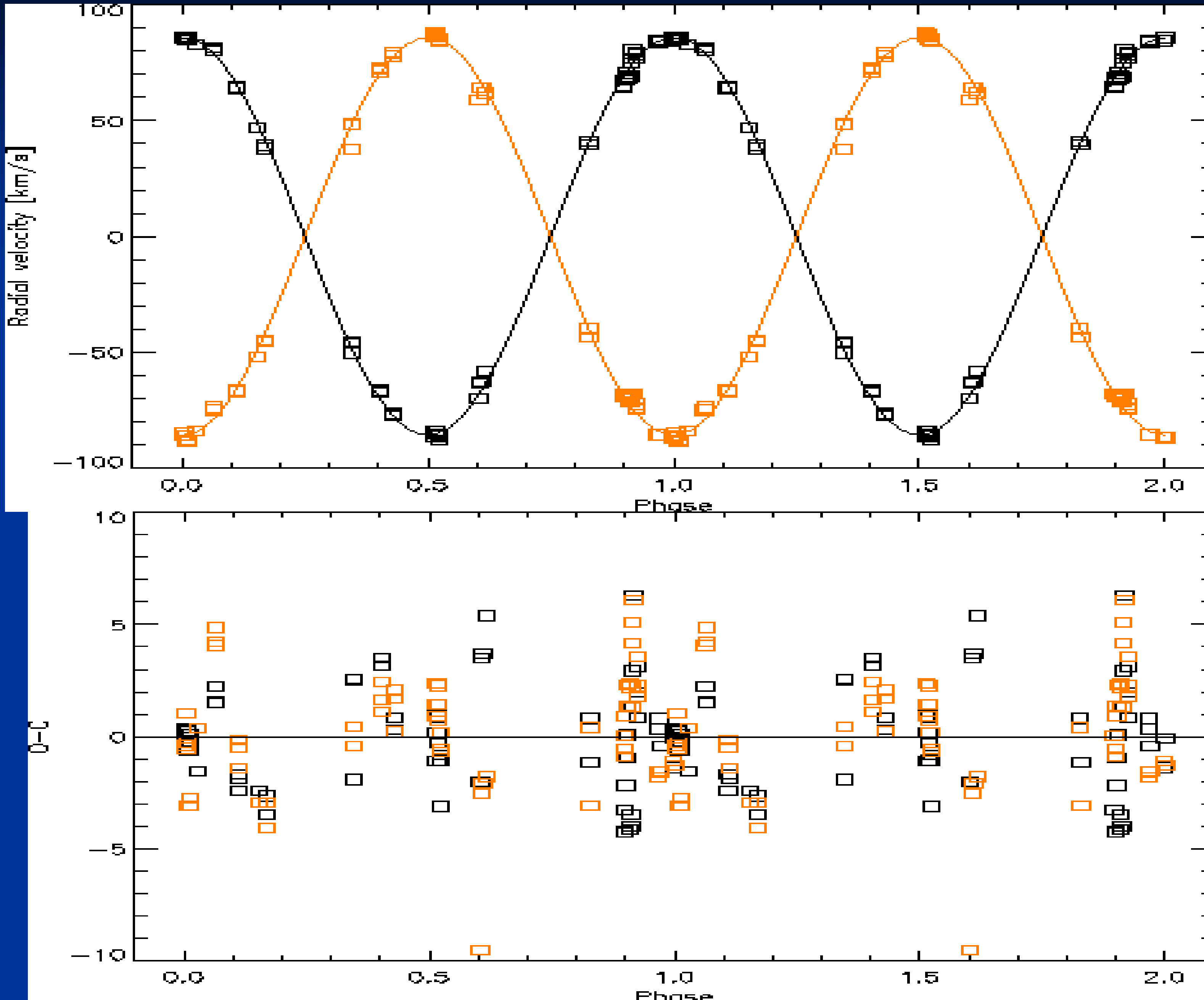
$K_1 = K_2 = K = 85.7 \pm 2$ km s^{-1}

$\gamma = 32.4 \pm 1.5$ km s^{-1}

i = 59º (see below)

The radial velocity curve, folded with the above orbital period, is shown in the next slide.

FOLDED VELOCITY CURVE AND O-C RESIDUALS



Spectral Analysis: Decontaminating

The spectra of Θ^1 Ori E, on which both line systems of the binary components are separated, show nearly identical Li I 6708 Å absorption lines with observed equivalent widths of about 0.14 Å, and clear Ca II K emission lines shifted in wavelength with velocities corresponding to the orbital motion of the binary. Both features are indicative of the stars' pre-main-sequence evolutionary stage.

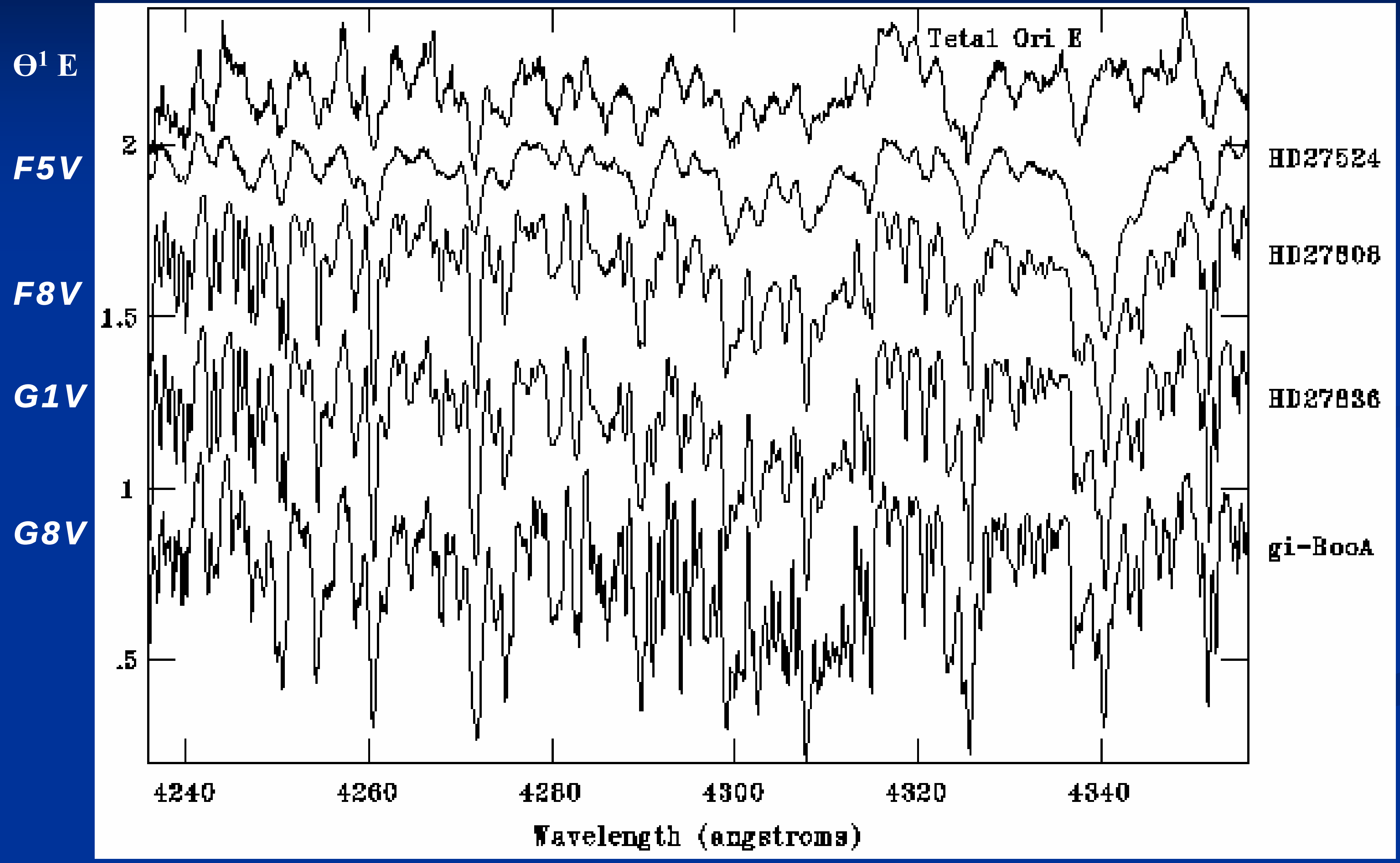
We produced a composite spectrum of Θ^1 Ori E by adding 12 individual spectra of the object, obtained on 2006 Jan 10, when the binary was near conjunction $\varphi \approx 0.98$ and the spectral line systems of the components were blended. Strong He I lines from Θ^1 Ori A (B0.5V, V = 6.75) are clearly present in this spectrum. Only He I λ4388 Å is not badly affected by nebular emission or strong absorption lines from Θ^1 Ori E itself. This line was used to estimate the light contribution from A to the composite spectrum of E at that wavelength (57%). The corresponding contribution at other wavelengths was assumed to be the spectrum of A convolved with a Raleigh scattering function. The convolved spectrum of star A, scaled to 57% at λ4388 Å, was then subtracted from the composite spectrum of E.

SPECTRAL CLASSIFICATION

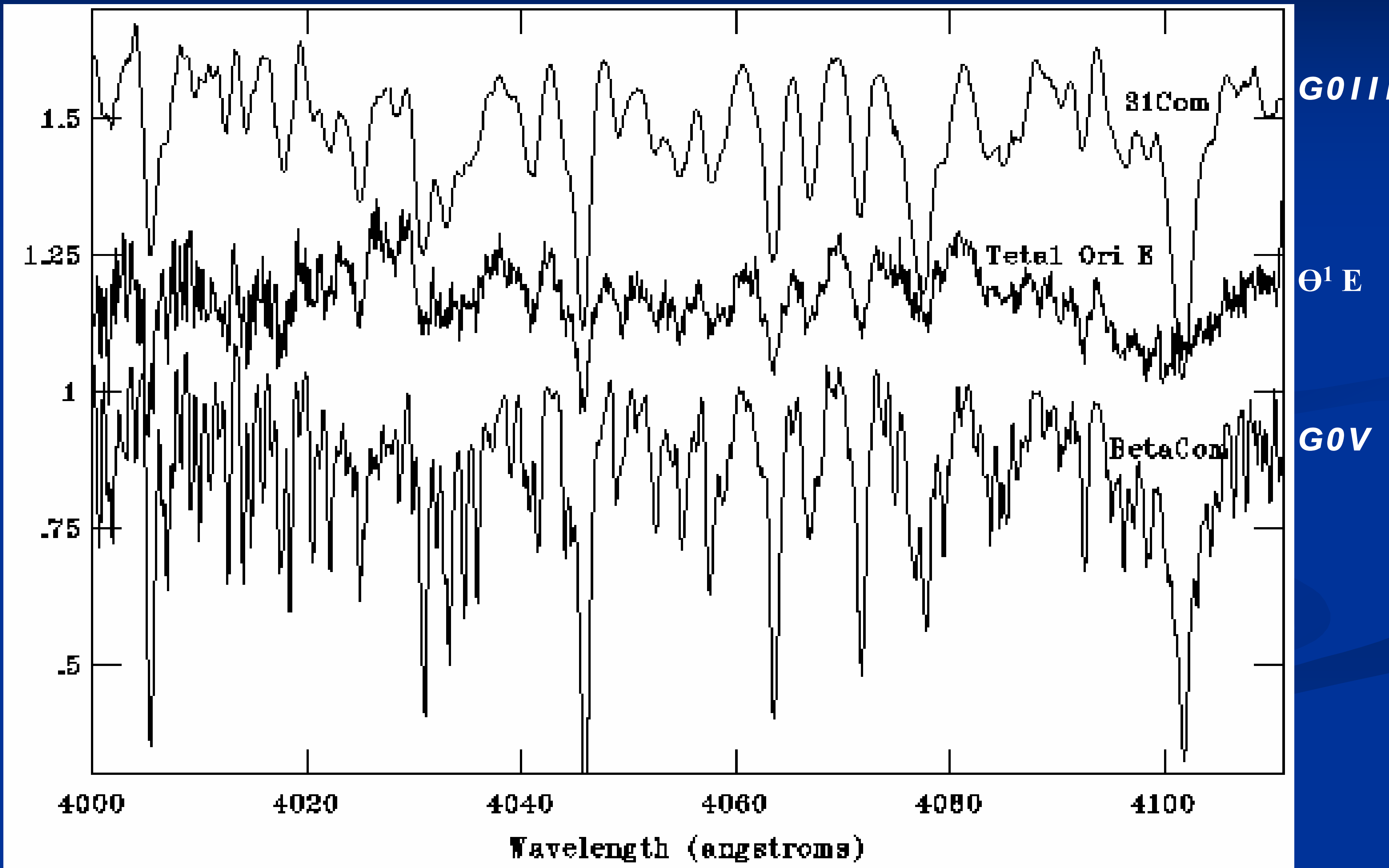
The composite and corrected spectrum of θ^1 Ori E was compared to the spectra of F5 to G8 main-sequence MK standards. The Balmer lines in the former are strongly affected by those from the nebula and from star A, so they can not be safely used. Otherwise, the spectrum of Θ^1 Ori A is consistent with its components being nearly identical and of spectral type around F8-G2, as shown in next slide.

The luminosity class is more precisely estimated. The main classical criterion arises from the comparison of FeI 4046 Å with Sr II 4078 Å (Morgan et al., 1978), which in θ1 Ori E is intermediate between the MK standards β Com (G0 V) and 31 Com (G0III), as shown in two slides ahead. The strength of many other luminosity sensitive lines, like the blend around λ4417 Å, also point towards a subgiant luminosity class.

SPECTRAL TYPE: The G-band and Hγ range



LUMINOSITY: The Sr II line at λ4078 Å



SPECTRAL CLASSIFICATION

We conclude that the binary components of θ^1 Ori E are pre-main-sequence stars of nearly identical F8-G2 IV spectral class.

In what follows, we adopt both stars to be G0IV

(although we will use intrinsic parameters of main sequence stars)

PHYSICAL PARAMETERS

We can safely assume that θ^1 Ori E components are identical and in circular orbit. Then, based on:

- Their adopted, identical spectral type (G0) here derived
- Their published K magnitude (6.90)
- The intrinsic color indices of G0 main sequence stars
- An assumed moderate interstellar extinction (Av=1.5)
- Siess *et al*. (2000) pre-main-sequence evolutionary tracks

the fallowing physical parameters for both binary components are obtained:

$M_{bol} = -0.12$ $R = 8.4\ R_\odot$ $M = 4.0\ M_\odot$

ORBITAL INCLINATION and ECLIPSES

Since the orbit is circular, the orbital velocity is constant

$V_{orb} = K\,(sin\ i)^{-1} = \pi\, a\,(P\,)^{-1}$.

The value of *sin i* is then obtained from Kepler's law, as a function of $P^{2/3}$ and $(M_1+M_2)^{1/3}$. Using the values here derived, we obtain an orbital inclination $\boldsymbol{i = 59^o}$ **.**

From the stellar radii here deduced, the minimum orbital inclination angle for grazing eclipses to occur is estimated to be 65^o, so no observable eclipses are predicted for this suspected variable star.

References

Allen, C.; Poveda, A. & Worley, C., 1974, *Rev.Mex.A.A.*, **1**, 101

Allen, C.; Poveda, A. & Hernández-Alcántara, A., 2004, *RevMexAA.Conf.Ser.*, **21**, 195

Bondar', N.I,; Vitrichenko, É.A. & Zakirov, M.M., 2000, *Astron. Letters*, **26**, 452

Costero, R.; Echevarría, J.; Poveda, A. & Richer, M., 2006, *IAU Communications* # 8669

Feigelson E.D. *et al*., 2002, *Ap.J*. **574**, 258

Felli *et al*., 1993, *A&A.S.* **101**, 127

Herbig,G.H., 1950, *ApJ*, **111**, 15

Hillenbrand, L.A., 1997, *A.J*. **113**, 1733

Hillenbrand, *et al*., 1998, *A.J*. **116**, 1816

Ku, W.H.-M., Raghini-Cohen, G. & Simon, M., 1982, *Science*, **215**, 61

Kukarkin, *et al*., 1982, "*New Catalogue of Suspected Variable Stars*" (Moscow: Nauka Publishing House, and http://www.sai.msu.su/groups/cluster/gcsv/nsv/)

Luhman, K.L. *et al*., 2000, *Ap.J*. **540**, 1016

McCaughrean, M.J. & Stauffer, J.R., 1994, *A.J*. **108**, 1382

Morgan, W.W.; Abt, H.A. & Topscott, J.W., 1978, "*Revised MK Spectral Atlas*" Yerkes Obs., U. Chicago & Kitt Peak Nat. Obs.

Muench, A.A., *et al*., 2002, *Ap.J*. **573**, 366

Parenago, P.A., 1954, *Trudy Stenberg Astr. Inst*., Vol. **25**

Prosser, C.F., *et al*., 1994, *Ap.J*., **421**, 517

Siess L., Dufour, E. & Forestini, M., 2000, *A&A*, **358**, 593