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A SUN IN THE SPECTROSCOPIC BINARY IM PEGASI, THE GUIDE STAR FOR THE *GRAVITY PROBE B* MISSION

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ABSTRACT

We present the first detection of the secondary of the spectroscopic binary system IM Pegasi (HR 8703), the guide star for the NASA-Stanford relativity gyroscope mission *Gravity Probe B*. In support of this mission, high-resolution echelle spectra of IM Peg have been obtained on an almost nightly basis. Applying the technique of least-squares deconvolution, we achieve very high signal-to-noise ratio line profiles and detect the orbit of the secondary of the system. Combining almost 700 new radial velocity measurements of both the primary and secondary of the system with previous measurements, we derive improved orbital parameters of the IM Peg system. Using these estimates along with the previously determined range of orbital inclination angles for the system, we find that the primary of IM Peg is a giant of mass $1.8 \pm 0.2\ M_\odot$, while the secondary is a dwarf of mass $1.0 \pm 0.1\ M_\odot$.

Subject headings: binaries: spectroscopic — stars: individual (IM Pegasi)

Online material: machine-readable table

1. INTRODUCTION

IM Pegasi (=HR 8703, HD 216489) is a long-period single-lined spectroscopic binary that has been classified as an RS Canum Venaticorum type by Hall (1976). The most recent determinations of the orbital parameters of the system have been made by Berdyugina et al. (1999, hereafter BIT99) and Fekel et al. (1999). Both these references give IM Peg an orbital period of ~24.65 days and a near-circular orbit ($e = 0.006 \pm 0.007$ from BIT99 and $e = 0.0$ from Fekel et al. 1999). As a prelude to Doppler imaging (see Berdyugina et al. 2000), BIT99 determined stellar parameters of the IM Peg primary based on model atmosphere analysis. They found the primary component of the system to be a K2 III star with an effective temperature of ~4450 K. Calculating $\log g = 2.4 \pm 0.1$ for the primary, and assuming a luminosity ratio of the primary to the secondary of ≥100, BIT99 estimated the secondary to be a K0 dwarf with a mass of $0.8 \pm 0.1\ M_\odot$ and the orbital inclination of the system to be $65° \leq i \leq 80°$.

Gravity Probe B (*GP-B*) is a polar-orbiting satellite designed to use gyroscopes to test with unprecedented accuracy two predictions of Einstein's theory of general relativity (Mester et al. 2004): the geodetic effect due to the curvature of space near Earth, and the Lense-Thirring or "frame dragging" effect due to the rotation of Earth.[11] Drifts in the gyroscopes are measured with respect to the optical centroid of the guide star IM Peg. However, IM Peg is a magnetically active star and consequently has dark spots on its surface, seen in the Doppler images of Berdyugina et al. (2000), covering 15% or more of the surface. Because the *GP-B* mission is designed to measure the mean drift of the gyroscope spin axes with a standard error of less than 0.5 mas yr^{-1}, even small contributions to the motions of the optical centroid must be reliably measured or bounded. In support of the *GP-B* mission, we are undertaking an intensive Doppler imaging survey of the primary component of IM Peg, to determine the extent to which spot activity on the surface of the primary could shift the optical centroid of the star and thus affect the accuracy of the *GP-B* experiment. These Doppler images will be presented in a forthcoming paper. As one of the results of this survey, we report here the first spectroscopic detection of the IM Peg secondary, obtained by means of the least-squares deconvolution technique (Donati et al. 1997). We also derive improved estimates of the orbital and stellar parameters for the system based on new radial velocity measurements of both the primary and the secondary.

2. OBSERVATIONS

In support of the *GP-B* mission, IM Peg is being observed nightly (when possible) using the Automatic Spectroscopic Telescope (AST) of Tennessee State University (Eaton & Williamson 2004), located at the Fairborn Observatory in Arizona. The AST is a 2 m Cassegrain telescope under complete computer control that is equipped with a fiber-fed echelle spectrograph of conventional white-pupil design. The observations give complete wavelength coverage from 4920 to 7110 Å at a resolution of ~37,000 (FWHM ~ 2 pixels). Although the observations of IM Peg have been ongoing since 2003 August, for this Letter we use only those spectra taken after a new fiber was installed to feed the spectrograph, in mid-September of 2004, markedly increasing system throughput. Our data set

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[11] Further information on the *Gravity Probe B* mission can be found at http://einstein.stanford.edu. It was launched in 2004 April and has a life expectancy of 17 months, the lifetime of its cryogen supply.

TABLE 1
HELIOCENTRIC JULIAN DATES OF NEW OBSERVATIONS AND RADIAL VELOCITY MEASUREMENTS OF THE PRIMARY AND SECONDARY COMPONENTS OF THE IM PEGASI SYSTEM

HJD (2,400,000+)	R.V.$_{primary}$ (km s^{-1})	R.V.$_{secondary}$ (km s^{-1})	Telescope
50,617.7301	...	38.0	NOT
50,618.6916	...	42.5	NOT
50,619.7147	...	47.0	NOT
50,620.6429	...	46.2	NOT
50,622.6684	...	37.8	NOT

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

includes over 90 nights of AST observations, with one to eight exposures per night (through to 2005 February); the average signal-to-noise ratio (S/N) of the individual spectra is ∼100 per pixel.

Between 1997 and 2004, over 100 observations of IM Peg were taken using the Soviet-Finnish echelle spectrograph (SOFIN) on the 2.56 m Nordic Optical Telescope (NOT) on La Palma, Canary Islands. The data were acquired and reduced as outlined previously in BIT99 and Berdyugina et al. (2000). The spectra give incomplete wavelength coverage from 5500 to 8500 Å at a resolution of ∼83,000 (∼2 or ∼3 pixels, depending on the CCD used) and an average S/N in the individual spectra of ∼200.

Over 120 observations of IM Peg were obtained between 2002 July 4 and 2004 November 3 at Lick Observatory. IM Peg was observed along with stars in the Doppler planet search project, using the 0.6 m Coudè Auxiliary Telescope and Hamilton spectrometer (Vogt 1987). Typical exposure times of 30 minutes produced spectra with a S/N of ∼100.

Finally, 24 observations of IM Peg were taken between 2004 September 23 and 30 with the University College London Echelle Spectrograph and the SEMPOL visitor instrument (Semel et al. 1993; Donati et al. 2003) at the 3.9 m Anglo-Australian Telescope (AAT). These observations gave complete wavelength coverage from 4340 to 6730 Å at a resolution of ∼70,000 (∼2.5 pixels) and were reduced using ESpRIT (Donati et al. 1997). The average S/N of the individual spectra was ∼150. A log of our new observations is given in Table 1.

3. RESULTS

3.1. *Radial Velocity of the Primary*

BIT99 used the NOT data from 1997 to determine the radial velocity of the IM Peg primary by cross-correlating the observed spectra with synthetic spectra of a similar spectral type. A similar process has been used here for our NOT data from 1998 to 2004 and all our AST and AAT data, using four spectral orders (within the wavelength range 6000–6750 Å). We have kept only those measurements that show a standard deviation in the radial velocity between the orders of less than 0.5 and 1.0 km s^{-1}, respectively, for the NOT and AST/AAT data (∼91% of observations). The average standard deviations of the three data sets (NOT, AAT, AST) are ∼0.3, ∼0.4, and ∼0.5 km s^{-1}.

Since the Lick observations were taken as part of the planet search project, the Doppler velocities were determined with the spectral synthesis technique described by Butler et al. (1996). This analysis makes use of an iodine absorption cell positioned in front of the spectrometer slit. A S/N of 100 is adequate to obtain a precision of 5 to 10 m s^{-1} in slowly rotating, chromospherically quiet main-sequence stars. However, IM Peg is a chromospherically active star with a high $v \sin i$ of 26.5 ± 0.5 km s^{-1} (BIT99), meaning that line centroiding in the Doppler analysis is much less precise. This, coupled with the activity and spots of the primary, means that for the Lick data the rms fit to the system is ∼560 m s^{-1}.

Overall, we have 489 new radial velocity measurements of the primary (99 NOT, 243 AST, 123 Lick, and 24 AAT) spanning from 1998 July to 2005 February.

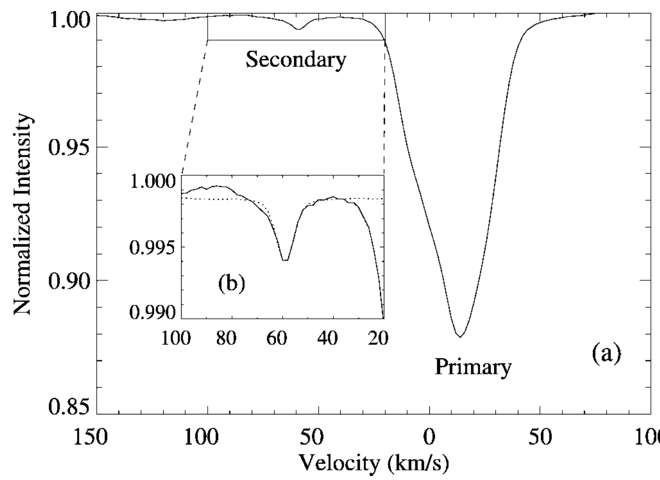

FIG. 1.—(*a*) Least-squares deconvolution profiles of the primary and secondary components of the IM Peg system obtained at the Anglo-Australian Telescope on 2004 September 24, at an orbital phase of 0.873; (*b*) LSD profile of the secondary compared with a scaled solar LSD profile created using the same line mask (*dotted line*).

3.2. *Radial Velocity of the Secondary*

Because no individual spectral line of the secondary could be detected in any of our spectra, a different approach was required to determine its radial velocity. Least-squares deconvolution (LSD) is a mathematical technique used to improve the S/N of data and employed in Doppler and Zeeman Doppler imaging (e.g., Donati et al. 2003). The technique combines up to several thousand photospheric lines in an echelle spectrum into a single, high signal-to-noise average profile (Donati et al. 1997).

We generated LSD profiles of IM Peg from our echelle data using a line list created from the Kurucz atomic database and ATLAS9 atmospheric models (Kurucz 1993a, 1993b) for a star with a photospheric temperature of 4500 K and a surface gravity of $\log g = 2.5$, very similar to the values for the IM Peg primary found by BIT99. An example of an LSD profile of IM Peg created using over 5500 photospheric lines from the AAT data with a S/N of over 2000 is given in Figure 1*a*. We similarly generated LSD profiles from the 1997–2004 NOT observations (using ∼150 photospheric lines) and from the 2004–2005 AST observations (∼1700 lines). The average S/N of the LSD profiles from the data sets is ∼1500 and ∼700 for AAT and AST/NOT. Gaussian profiles were then fitted to the secondary's LSD profiles. The centroids of the Gaussians were taken as the secondary's radial velocity.

We have obtained 209 radial velocity measurements of the secondary spanning from 1997 June to 2005 February (66 NOT,

TABLE 2
IM Pegasi Orbital Parameters

Element	Fekel et al. 1999	BIT99	This Work
P (days)	24.648944 ± 0.000075	24.64880 ± 0.00005	24.64877 ± 0.00003
e	0.0	0.006 ± 0.007	0.0
K_1 (km s^{-1})	34.30 ± 0.17	34.42 ± 0.06	34.29 ± 0.04
$a_1 \sin i$ ($R_\odot$)	16.715 ± 0.083	16.76 ± 0.04	16.70 ± 0.02
$f_1(m)$ ($M_\odot$)	0.1033 ± 0.0015	0.1042 ± 0.0006	0.1030 ± 0.0004
K_2 (km s^{-1})	…	…	62.31 ± 0.06
$a_2 \sin i$ ($R_\odot$)	…	…	30.34 ± 0.03
$f_2(m)$ ($M_\odot$)	…	…	0.618 ± 0.002
$T_{\rm conj}$ (HJD)	…	2,450,342.883 ± 0.007	2,450,342.905 ± 0.004
M_2/M_1	…	0.5 ± 0.1[a]	0.550 ± 0.001
$M_1 \sin^3 i$ ($M_\odot$)	…	…	1.486 ± 0.007
$M_2 \sin^3 i$ ($M_\odot$)	…	…	0.818 ± 0.005

[a] Determined from mass-mass diagram; see BIT99 for details.

127 AST, and 16 AAT). Our radial velocity measurements of both the primary and secondary are given in Table 1.

3.3. *Orbital Parameters and Mass Estimates*

Combining our new radial velocity observations with previously published measurements spanning from 1919 to 1997 from BIT99 (and references therein) and Fekel et al. (1999), we used the FOTEL 3 program (Hadrava 1995) to determine improved orbital parameters of the system, assuming an eccentricity of 0.0. All velocity measurements were given equal weighting. Because of the method used to derive the radial velocities, the γ-velocity of the Lick observations is close to 0 km s^{-1}, whereas the average value for the other data sets is -14.04 km s^{-1}. For consistency, we shifted the Lick measurements by -14.04 km s^{-1}.

The new orbital parameters for the IM Peg system are given in Table 2, along with the previous determinations of BIT99 and Fekel et al. (1999). We plot the new orbital solution in Figure 2.

Using the calculated orbital parameters for the secondary, it is now possible to determine the mass ratio of the two stars: $M_2/M_1 = 0.550 \pm 0.001$. This ratio is consistent with the one estimated by BIT99 from a mass-mass diagram for the system (0.5 ± 0.1). Our estimates of $M \sin^3 i$ are 1.486 ± 0.007 and 0.818 ± 0.005 $M_\odot$ for the primary and secondary, respectively, where i is the orbital inclination angle. Using the orbital inclination estimate of $65° \leq i \leq 80°$ from BIT99, we calculate the masses of the primary and secondary of the system to be 1.6–2.0 and 0.9–1.1 $M_\odot$, respectively, somewhat higher than the calculations of BIT99. This is due to BIT99's assumption that the luminosity ratio of the primary to the secondary is ≥100; however, as we show in § 3.4, this ratio is too high.

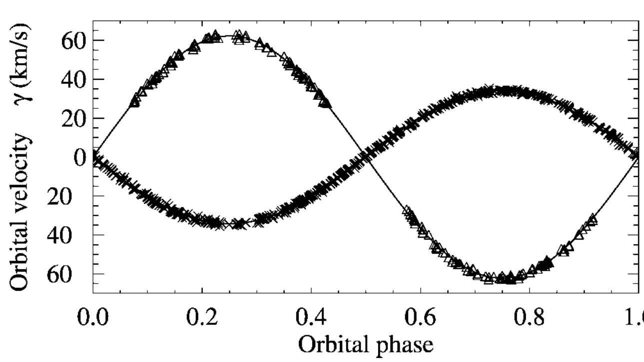

Fig. 2.—New orbital solution for IM Peg. Crosses represent radial velocity measurements of the primary, and triangles those of the secondary.

3.4. *Luminosities of the Primary and Secondary*

The flux ratio of the two components of the IM Peg system at the average wavelength of the LSD profile can be estimated from the central line depth of the LSD profile of the secondary, that is, from

$$1 - df = \frac{F_p^c + F_s}{F_p^c + F_s^c}, \quad (1)$$

where F_p^c and F_s^c are the continuum flux contributions from the primary and secondary, respectively, F_s is the full spectrum contribution from the secondary, d is the central line depth of a solar LSD profile, and f is the scale factor used to fit the solar LSD profile to the LSD profile of the secondary (see Fig. 1*b*). Because LSD profiles are normally computed with each contributing line weighted by its model line depth, these profiles are dependent upon the line mask used. Consequently, the flux ratio depends on the line depths in the model. To avoid this dependence, we have created the solar LSD profile (from an observation of the Moon taken on the same night as the IM Peg observation with the same instrumental setup) using the same line mask as that used to create the IM Peg LSD profiles (i.e., $T_{\rm eff} = 4500$ K and $\log g = 2.5$).

To determine the flux ratio, equation (1) can be simplified to

$$\frac{F_p^c}{F_s^c} = \frac{1-f}{f}. \quad (2)$$

As this flux ratio is dependent upon both the radii of the stars and their effective temperatures, we have to calculate equation (2) for two different wavelengths in order to determine both the radius and the effective temperature of the secondary. To do this we have taken one of the AAT observations (on 2004 September 24) and created two LSD profiles. The blue LSD profile was created from those photospheric lines with wavelengths $\lambda < 5000$ Å, and the red LSD profile from lines with $\lambda > 5000$ Å. The limiting wavelength of 5000 Å was chosen so that both LSD profiles were of a similar S/N. The average wavelength for the blue LSD profile was 4720 Å, for which the fitted solar LSD profile (also created using lines with $\lambda < 5000$ Å) gave a scale factor $f = 0.023 \pm 0.002$. The average wavelength of the red LSD profile was 5570 Å with a scale factor $f = 0.018 \pm 0.002$. Thus the flux ratios (from eq. [2]) for the blue and red wavelengths are 43 ± 4 and 55 ± 6, respectively. Given the radius and temperature of the primary of IM Peg of $13.3 \pm 0.6\ R_\odot$ and 4550 ± 50 K from BIT99, the Planck blackbody radiation formula can be used along with the blue and red flux ratios to determine a range of possible radii and temperatures for the secondary of IM Peg. This is shown as the shaded area in Figure 3. The range of possible radii and temperatures is quite large. However, a further restriction can be placed on the allowed region if we assume that the secondary is a main-sequence star and use a simple linear fit to effective temperature and radius of main-sequence stars of around 1.0 $M_\odot$,

$$T_{\rm eff} = 3320\left(\frac{R}{1\ R_\odot}\right) + 2320 \pm 100\ \text{K}, \qquad (3)$$

where $T_{\rm eff}$ is the effective temperature and R is the stellar radius (based on data taken from Lang 1992). The three parallel lines in Figure 3 show equation (3) (including its error range). The area where these lines overlap the shaded area in Figure 3 displays the allowed combinations of radius and temperature for the IM Peg secondary. Thus the secondary should have a radius of $1.00 \pm 0.07\ R_\odot$ and an effective temperature of 5650 $\pm$ 200 K, giving a luminosity of $L_s = 0.9 \pm 0.3\ L_\odot$. These values are in excellent agreement with our derived mass of 1.0 $\pm$ 0.1 $M_\odot$ for a main-sequence star.

Using the visual magnitude of the IM Peg system around the time of the AAT observations ($m_V = 5.89 \pm 0.02$; G. W. Henry 2005, private communication), we can estimate the total luminosity of the system. With a distance to IM Peg of 97 $\pm$ 6 pc (Lestrade et al. 1999) and the bolometric correction for a K2 giant from Lang (1992) of $BC_V = -0.6$, we find $M_{\rm bol} = 0.36 \pm 0.15$. This corresponds to a total luminosity of $L_{\rm tot} = 55 \pm 9\ L_\odot$. Combining this with the secondary luminosity (L_s) gives a luminosity for the primary of $L_p = 54 \pm 9\ L_\odot$ and a luminosity ratio of the primary to the secondary of ~60.

As expected, our calculated luminosity of the secondary agrees well with the luminosity of a main-sequence dwarf of $1.0 \pm 0.1\ M_\odot$; however, the luminosity of the primary (54 $\pm$ 9 $L_\odot$) is significantly below that of a K2 giant (~79 $L_\odot$; Lang 1992). The reduced luminosity of the primary is obviously due to dark spot features on the stellar surface. The unspotted magnitude of the primary was calculated by BIT99 to be $V_0 = 5.55 \pm 0.05$. Given $m_V = 5.89 \pm 0.02$ (ignoring the minor contribution from the secondary), the luminosity of the primary at the time of our AAT observation is 73% $\pm$ 6% of the unspotted luminosity. This compares very well with the 70% $\pm$ 11% difference in our measurement of the primary's luminosity from that of a K2 giant given by Lang (1992).

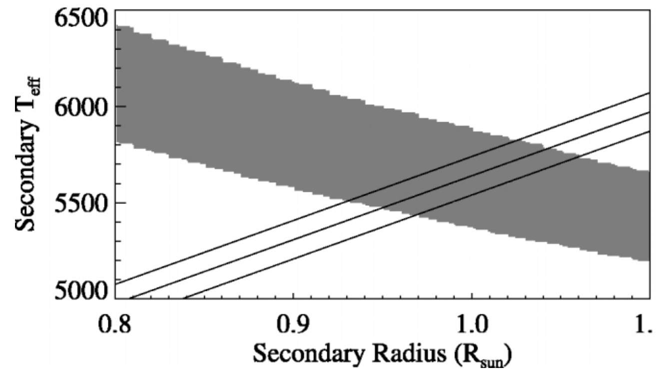

FIG. 3.—Graph of possible radii and temperatures for the secondary of IM Peg. The shaded area shows possible values based on the Planck blackbody radiation formula given the red and blue flux ratios (see § 3.4). The three parallel lines represent eq. (3).

4. CONCLUSIONS

In this Letter we have used the technique of least-squares deconvolution to produce very high S/N profiles of the spectroscopic binary IM Peg. These LSD profiles allowed us to make the first spectroscopic detections of the secondary of the system. Using new radial velocity measurements of both the primary and the secondary, we have derived improved orbital parameters for the system. An estimate of the orbital inclination of the system has enabled us to determine that the primary is a giant of $1.8 \pm 0.2\ M_\odot$, while the secondary is a dwarf of $1.0 \pm 0.1\ M_\odot$.

More generally, we have demonstrated that the high-S/N mean line profiles produced by the LSD technique offer a useful tool for the detection of faint secondaries in spectroscopic binary systems and for the subsequent determination of their orbital and stellar parameters.

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