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WASP-12b: the hottest transiting extra-solar planet yet discovered

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ABSTRACT

We report on the discovery of WASP-12b, a new transiting extrasolar planet with $R_{pl} = 1.79 \pm 0.09 R_J$ and $M_{pl} = 1.41 \pm 0.11 M_J$. The planet and host star properties were derived from a Monte Carlo Markov Chain analysis of the transit photometry and radial velocity data. Furthermore, by comparing the stellar spectrum with theoretical spectra and stellar evolution models, we determined that the host star is a super-solar metallicity ([M/H] = 0.3 $^{+0.05}_{-0.15}$), late-F ($T_{\text{eff}} = 6300^{+200}_{-100}$ K) star which is evolving off the zero age main sequence. The planet has an equilibrium temperature of $T_{eq} = 2516$ K caused by its very short period orbit ($P = 1.09$ days) around the hot, 12th magnitude host star. WASP-12b has the largest radius of any transiting planet yet detected. It is also the most heavily irradiated and the shortest period planet in the literature.

Subject headings: stars: planetary systems – techniques: radial velocities – techniques: photometric

1. Introduction

Transiting extra-solar planets have provided tremendous information about the properties of planets outside our Solar System. Since 2006, a burst of new planet discoveries have been reported. We are now beginning to see the variety of exoplanets which exist in the Galaxy and to classify them based on their properties. Furthermore,
due to the increasing number of planets being discovered and due to the detailed, multi-wavelength follow-up of a handful of very bright transiting systems (e.g. HD 209458, HD 189733), we are able to provide strong observational tests of theoretical models of planet formation and evolution.

Exotic planets are particularly important because they push the boundaries of our theoretical understanding. HD 209458b, for example, confounded theorists with its large radius (Brown et al. 2001). Since its discovery, a class of similar planets have been found suggesting these highly-irradiated, low-density planets are not rare. Here, we report on the discovery of a new extreme transiting extra-solar planet with a short orbital period, enlarged radius, and super-solar metallicity host star.

In this paper, we first describe all the observations we obtained to detect and analyse the transiting star-planet system (§2). We describe the data analysis in §3 where we present the properties of the planet and its host star. Finally in §4, we discuss the planet properties in the context of current theoretical understanding of planet formation.

2. Observations

2MASS J063032.79+294020.4 (hereafter WASP-12) is a bright F9V star. It has been identified in several northern sky catalogues which provide broad band optical (Zacharias et al. 2004) and infra-red 2MASS magnitudes (Skrutskie et al. 2006) and proper motion information. Coordinates and broad band magnitudes of the star are given in Table 1.

2.1. SuperWASP Photometry

Time series photometry of WASP-12 was obtained in the 2004 and 2006 seasons with the SuperWASP-N camera located on La Palma, Canary Islands (Pollacco et al. 2006). In 2004, when the target was first observed, only 820 photometric measurements were obtained between 2004 August and 2004 September. However, the same fields were observed again in 2006 after upgrades to the telescope mount and instrument. During the 2006 season, the target was observed in the field-of-view of two separate cameras, and a total of 5573 photometric brightness measurements were obtained between 2006 November and 2007 March. The data obtained in both seasons were processed with a custom built data reduction pipeline described in Pollacco et al. (2006), and the resulting light curves were analysed using a modified box least-squares algorithm (Collier Cameron et al. 2006; Kovács et al. 2002) to search for the planetary transit signature.

The combined SuperWASP data showed a significant periodic dip in brightness with a period, $P = 1.091$ days, duration, $\tau \sim 2.7$ hours, and depth, $\delta \sim 14$ mmag. The improvement in $\chi^2$ of the box-shaped transit model over the flat light curve was $\Delta \chi^2 = 719$ and the signal-to-rednoise (Pont et al. 2006) was $\text{SN}_{\text{red}} = 15.6$. A total of 23 partial or full transits were captured by SuperWASP.

There were no obvious objects blended with WASP-12 in the SuperWASP aperture, and the detected transit event was significant, therefore, WASP-12 was classed as a high priority target needing further study. In Figure 1, we show the phase-folded light curve of the SuperWASP data, adopting the ephemeris resulting from the box-least squares analysis on the combined light curve.

2.2. Follow-up Multi-band Photometry

After identification as a high priority transit candidate, follow-up photometry of WASP-12 was obtained using two additional telescopes with high spatial resolution ($< 1''$/pixel) compared to SuperWASP (13.7''/pixel). We obtained observations of WASP-12 and the surrounding region during the predicted time of transit to confirm that there are no eclipsing binaries within an arcminute of WASP-12 that may have caused of the transit signal in the SuperWASP data. WASP-12 also appears to be a single star at the resolution provided by these data. The closest companion is 9'' from the target and has a magnitude of $V \sim 18$. Encouraged by this, we then obtained complete $B$, $I$, and $z$-band light curves of the transit. A detailed description of the follow-up photometry is described below.

2.2.1. Tenagra Telescope photometry

WASP-12 was observed using the fully robotic, Tenagra II, 0.81m f/7 Ritchey-Chretien telescope sited in Arizona, USA. The science camera con-
Table 1: Stellar Parameters for WASP-12. The broad band magnitudes are obtained from the NOMAD 1.0 catalogue. The stellar parameters are derived from our spectral synthesis of observed spectra of WASP-12 (see §3.1).

| Parameter | WASP-12 |
|-----------|---------|
| RA(J2000) | 06:30:32.79 |
| Dec(J2000) | +29:40:20.4 |
| B         | 12.11 ± 0.08 |
| V         | 11.69 ± 0.08 |
| I         | 11.03 ± 0.08 |
| J         | 10.477 ± 0.021 |
| H         | 10.228 ± 0.022 |
| K         | 10.188 ± 0.020 |
| $T_{\text{eff}}$ | 6300$^{+200}_{-100}$ K |
| $[M/H]$   | 0.30$^{+0.05}_{-0.15}$ |
| log $g$   | 4.38 ± 0.10 |
| $v \sin i$ | < 2.2 ± 1.5 km/s |

Fig. 1.— The SuperWASP discovery light curve of WASP-12 phase-folded with a period, $P = 1.09142$ days and epoch, $T_0 = 2454476.2321$.

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2IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.
Sloan z’ band on the night of 18 February 2008. We employed 2×2 binning (0.27”/pixel) and used a 10s exposure time for all observations. The night was photometric, and the pointing was stable. The target star did not drift more than a few pixels throughout the transit which allowed for very accurate differential photometry.

The images were debiased, flat-fielded, and corrected for fringing using the standard RATCAM processing pipeline. IRAF DAOPHOT was then used to obtain aperture photometry of the target and four, non-variable nearby comparison stars using a 15 pixel radius aperture. The comparison stars were chosen primarily for brightness from within the limited FOV (4.6’ × 4.6’) of the camera and are not necessarily matched in color to the target. The differential photometry was performed in the same way as described above for the Tenagra data, and the resulting out-of-eclipse light curve has 2.5 mmag precision. The z-band and B-band transit light curves obtained via follow-up photometry are plotted in Figure 2.

### 2.3. SOPHIE Spectroscopy

High resolution spectroscopy of WASP-12 was obtained between 2008 February 12–22 with the SOPHIE spectrograph (Bouchy et al. 2006) on the 1.93m telescope at the Observatoire de Haute Provence. We used the same observing program and instrument set-up as for other SuperWASP planets discovered in the northern hemisphere (Pollacco et al. 2008; Christian et al. 2008; West et al. 2008).

The weather was clear and reasonably stable throughout the run, although there were some fluctuations in seeing and transparency. Therefore, we adopted exposure times of 900s and 1080s depending on the transparency. This allowed us to achieve a signal-to-noise (S/N) per resolution element (at 5500Å) of 30–45 in all the spectra. The S/N values for all the spectra are listed in Table 2. The spectra were processed in real time with the SOPHIE instrument control and data reduction software, and the RV measurements were obtained using a weighted cross-correlation method (Baranne et al. 1996; Pepe et al. 2005). To do this, we used a numerical mask constructed from the solar spectrum atlas corresponding to a G2V star.

The Moon was bright over most of the run thus contaminating the spectra with scattered light. We removed its velocity signature (according to the procedure described in Pollacco et al. (2008)) from all the spectra. We then fit the resulting cross-correlation function from each spectrum with a Gaussian to derive a value for the central RV, the full width half maximum (10.15–10.30 km s⁻¹), and the peak amplitude or Contrast (28.60–29.44%). The uncertainties for all RV measurements were derived using an empirical relation applicable to SOPHIE spectra taken in the high efficiency mode (West et al. 2008; Bouchy et al. in prep).

In this way, we obtained 21 RV measurements of WASP-12 over ten nights which have typical uncertainties of ~ 10 m s⁻¹. The RV measurement obtained from each spectrum is listed in Table 2 along with the derived uncertainty. These data have a standard deviation of 130 m s⁻¹, significantly greater than the individual uncertainties, and they vary sinusoidally when folded on the period derived from the transit photometry (Figure 4).

Finally, any asymmetries in the line profiles were explored by measuring the velocity span of the line-bisector (Gray 1988) according to the technique outlined in Queloz et al. (2001). These measurements, also listed in Table 2, show no correlation with radial velocity (Figure 3), therefore it is unlikely that the observed RV variations are caused by star spots on the stellar surface or by blending with an eclipsing binary star in the system or close to the line-of-sight.

Thus, we conclude that the observed RV variations are caused by the gravitational influence of a planetary-mass object orbiting WASP-12. Figure 4 shows a plot of the RV measurements phase-folded on the ephemeris given in Table 3 and over-plotted with the best fitting model radial velocity curve which is derived as described in the analysis section (3.2).

### 2.4. Additional Spectroscopy

The SOPHIE spectra were obtained in the high efficiency (HE) mode which is known to suffer from problems with corrections for the blaze shape. According to the data products website, a residual
Fig. 2.— Differential $z$-band (top) and Tenagra $B$-band (bottom) photometry of WASP-12 during the transit. An offset has been added to the $B$-band data for clarity. The data are phase-folded with the ephemeris given in Table 3. Overplotted are the best fit model transit light curves using the formalism of Mandel & Agol (2002) applying the limb darkening coeffs from Claret (2000, 2004).

Table 2: The radial velocity measurements of WASP-12 obtained with SOPHIE spectrograph.

| BJD     | V_r     | $\sigma_{RV}$ | S/N  | Bisector |
|---------|---------|---------------|------|----------|
|         | (km s$^{-1}$) | (km s$^{-1}$) |      | (km s$^{-1}$) |
| 2454509.38633 | 18.9231 | 0.0088 | 44.3 | 0.015 |
| 2454509.53836 | 19.0845 | 0.0112 | 34.9 | 0.047 |
| 2454510.40255 | 18.8497 | 0.0102 | 38.0 | 0.046 |
| 2454511.29105 | 18.9394 | 0.0082 | 47.4 | 0.056 |
| 2454511.36791 | 18.9008 | 0.0090 | 43.0 | 0.047 |
| 2454511.40825 | 18.8582 | 0.0090 | 43.3 | 0.047 |
| 2454511.53661 | 18.8945 | 0.0108 | 36.1 | 0.005 |
| 2454512.28835 | 19.0648 | 0.0088 | 44.0 | 0.057 |
| 2454512.30278 | 19.0429 | 0.0084 | 45.6 | 0.031 |
| 2454512.31570 | 19.0298 | 0.0096 | 40.1 | 0.010 |
| 2454512.32867 | 19.0064 | 0.0090 | 42.7 | 0.033 |
| 2454512.34174 | 18.9973 | 0.0088 | 44.2 | 0.030 |
| 2454512.35470 | 18.9778 | 0.0086 | 45.2 | 0.036 |
| 2454512.40579 | 18.9176 | 0.0090 | 42.6 | 0.038 |
| 2454512.43225 | 18.9124 | 0.0088 | 44.4 | 0.047 |
| 2454512.44721 | 18.8936 | 0.0086 | 45.6 | 0.018 |
| 2454513.32972 | 19.0957 | 0.0128 | 29.7 | 0.079 |
| 2454514.30357 | 19.2105 | 0.0130 | 29.6 | -0.001 |
| 2454515.27220 | 19.3213 | 0.0106 | 36.1 | -0.018 |
| 2454516.40210 | 19.2961 | 0.0128 | 29.8 | 0.067 |
| 2454519.43071 | 19.1968 | 0.0088 | 44.3 | 0.038 |

Fig. 3.— Line-bisector velocity versus radial velocity measured from all the observed SOPHIE spectra. We adopt uncertainties of twice the radial velocity uncertainty for all bisector measurements. There is no correlation between these two parameters indicating the radial velocity variations are not caused by stellar activity or line-of-sight binarity.

Fig. 4.— The SOPHIE radial velocity curve of WASP-12 phase-folded with the ephemeris given in Table 3. The solid line is the best model curve resulting from the orbital parameters of the system derived from the MCMC analysis in §3.2. The systemic RV value is shown by the dotted line.
blaze effect remains in the reduced spectra at the 5% level\( ^{4} \). These data provide exceptional radial velocity precision, but they are not always suitable for determining stellar parameters. For example, the effective temperature is strongly constrained by the wings of the Hα line, and for hot stars with broad Hα wings, the residual instrumental features in the SOPHIE HE spectra lead to large uncertainties on this parameter. Therefore, in addition to the 21 SOPHIE spectra which were used primarily to measure the radial velocity signature of the orbiting planet, several additional spectra of WASP-12 were obtained and used in deriving independent measurements of the stellar parameters of the host star. The additional spectroscopic observations are described below, and the derivation of the stellar parameters from all available spectra are described in \( ^{3.1} \).

### 2.4.1. Isaac Newton Telescope spectra

Two individual spectra of WASP-12 were obtained on 2008 April 22 with the 2.5m Isaac Newton Telescope and Intermediate Dispersion Spectrograph (IDS). The longslit data were taken with the H1800V grating using a 1.2\(' \) slit which resulted in a resolution of \((R \sim 8000)\). A signal-to-noise of > 50 was achieved in both individual spectra by taking 900s exposures. The spectrum was centered at 6500Å and covered the region from 6200–7000Å, thereby providing measurements of Hα, the Li I doublet at 6708Å and many narrow metal lines. Biases and lamp flats were obtained at the beginning of the night and Neon-Copper-Argon arcs were taken just before and just after the WASP-12 observations. The spectra were reduced in a standard way using the IRAF longslit package. We then averaged the two individual spectra and continuum normalized the composite observation before fitting for the stellar parameters.

### 2.4.2. Telescopio Nazionale Galileo spectra

We observed the target again on 29 April 2008 using the high efficiency echelle spectrograph, SARG, mounted on the 3.58 m Telescopio Nazionale Galileo (TNG) telescope. These data were taken as part of the Canarian Observatories International Time Programme. Three consecutive 1800 second exposures were taken using the yellow filter and grism. The spectra were binned 2×1 in the spatial direction at the time of observation to reduce the readout time. A slit width of 0.8\(' \) was adopted which resulted in a spectral resolution of R~57000. Calibration images, including bias frames, lamp flat-field frames, and Thorium-Argon arcs, were taken at the beginning of the night and used in processing the target spectra with the REDUCE echelle data reduction package (Piskunov & Valenti 2002). Special care was taken to provide an accurate flat-fielding of the data. The three individual reduced spectra were averaged on an order-by-order basis to produce a final merged spectrum which was then used in the determination of the stellar parameters described in \( ^{3.1} \).

### 3. Analysis

#### 3.1. Spectroscopic analysis

Three spectra of WASP-12 were derived from observations with the SARG, SOPHIE, and IDS spectrographs. Each independent spectrum was compared with synthetic spectra to determine the effective temperature \( T_{\text{eff}} \), gravity \( \log g \), metallicity, [M/H], and projected stellar rotation \( v \sin i \) of WASP-12. Our spectral synthesis technique closely follows the procedure of Valenti & Fischer (2005) (hereafter VF05), and a detailed description can be found in Stempels et al. (2007).

Two additional parameters, microturbulence and macroturbulence, are incorporated into the spectral synthesis to characterise turbulent mixing and convection in the upper layers of stellar atmospheres (Gray 1988). Their chosen values affect the derived stellar properties such that microturbulence anti-correlates strongly with metallicity, and macroturbulence affects the line broadening, and therefore the \( v \sin i \) measurement. In our spectral synthesis, we closely follow VF05, so that our results can be compared directly with this extensive spectroscopic analysis of planet-hosting stars. For the microturbulence, we adopt their value of \( v_{\text{mic}} = 0.85 \text{ km s}^{-1} \), but we note that other empirical studies of main sequence F-stars suggest higher values for \( v_{\text{mic}} \) (see Montalbán & D’Antona 2007). For the macroturbulence, we use the empirical linear relation with temperature provided in VF05 to derive a value of \( v_{\text{mac}} = 4.8 \text{ km s}^{-1} \). However, larger values are not excluded for hot
stars like WASP-12. This is due to the difficulty in accurately measuring macroturbulence for early type stars where rotational broadening typically dominates the line widths. Furthermore, only 79 stars in the VF05 sample have $T_{\text{eff}} > 6200$ K, so the empirical relation is not very well defined in this regime.

We used the SARG data to derive our best measurement of the parameters of the host star. This spectrum is of high resolution and good quality with no known residual instrumental features. Four spectral regions (shown in Figure 5) were selected for the fit because they are particularly sensitive to one or more of the parameters we aim to derive. A simultaneous fit to these four regions of the spectrum yielded a $T_{\text{eff}} = 6290$ K, $\log g = 4.38$, and $[\text{M/H}] = 0.30$. The line broadening was equivalent to that of the spectral resolution, therefore we were only able to derive an upper limit on the rotational broadening of $v \sin i < 2.2$ km s$^{-1}$. This is derived by subtracting (in quadrature) the estimated value of macroturbulence (4.8 km s$^{-1}$) from the width of the smallest resolvable resolution element (5.3 km s$^{-1}$ at $R=57000$). A comparison of the observed and best fitting model spectrum is shown in Figure 5 and the final stellar parameters are listed in Table 1. We derive uncertainties on these properties based on the range of values measured from the additional analysis of the IDS and SOPHIE data.

In the SOPHIE spectrum, we simultaneously fit the same four spectral regions given above and find $T_{\text{eff}} = 6175$ K, $\log g = 4.36$, and $[\text{M/H}] = 0.15$. We also measure a $v \sin i = 4.5$ km s$^{-1}$. Again, we believe this value is only an upper limit. The IDS spectrum spanned the region of H$\alpha$ and surrounding metal lines. In this region, there are no strongly gravity-sensitive features, therefore, we fixed the $\log g = 4.36$, which was determined from the SOPHIE observations, and solved for the stellar temperature, $T_{\text{eff}} = 6495$ K, and metallicity, $[\text{M/H}] = 0.16$. The resolution was too low to measure $v \sin i$.

In summary, we made three independent measurements of the properties of WASP-12 by comparing spectroscopic observations of the star to model spectra. In all three analyses, we find that WASP-12 is a hot, slowly rotating, metal rich, dwarf star. We adopt the results from the analysis of the SARG spectrum as our final values for the parameters of WASP-12 and the uncertainties on the stellar parameters from the range of values that were determined in the three different analyses.

3.2. Deriving Planet and Host Star Parameters

The multi-band light curves and radial velocity curve of WASP-12 were analysed simultaneously in a Markov-chain Monte Carlo (MCMC) based routine designed specifically to solve the multivariate problem of transiting star-planet systems. The routine is described in detail in Collier Cameron et al. (2007) and Pollacco et al. (2008). The results of the box-least squares analysis to the SuperWASP photometric data (described in §2.1) provide an initial estimate of the light curve parameters. We also initially assume an eccentricity of 0.02, a systemic RV equal to the mean of the velocity data, and a velocity amplitude derived by fitting a sinusoidal velocity variation to the observed RVs by minimizing $\chi^2$. To derive a first guess for the stellar mass, we interpolate the super-solar metallicity ($Z=0.03$, $[\text{M/H}] = 0.2$), zero-age main sequence temperature-mass relation from Girardi et al. (2000) at the stellar temperature derived in the previous section, $T_{\text{eff}} = 6300$ K. We adopt a stellar mass of $1.28 \, M_\odot$ as the initial value for this parameter.

Via the MCMC approach, the routine repeatedly adopts trial parameters until it converges on the set of values which produce the best model velocity curve and model light curves. The model light curves are generated from the analytic transit formulas found in Mandel & Agol (2002) (adopting the small-planet approximation) and using the limb darkening coefficients for the appropriate photometric filters from Claret (2000, 2004). The sum of the $\chi^2$ for all input data curves with respect to the models is the statistic used to determine goodness-of-fit. The routine also produces 1$\sigma$ uncertainties on all the parameters.

3.2.1. Evolutionary Status of the Host Star

We ran the MCMC code initially using the SuperWASP light curve, the $B$ and $z$-band follow up photometry, and the SOPHIE radial velocity curve as input data sets. We ran the code without imposing the main sequence prior on the overall $\chi^2$.
Fig. 5.— Observed SARG spectrum (grey) overplotted by the best fitting theoretical model spectrum (solid black line). The top panel shows the region around the Mg b triplet (5160-5190 Å), the second panel is the region around the Na I D doublet (5850-5950 Å), the third panel shows the region from 6000-6210 Å with a large number of metal lines, and the bottom panel is the region around the Hα line (6520-6600 Å). These regions are modelled simultaneously with spectral synthesis to derive the parameters of the host star. The light grey regions of the spectrum are used to determine the continuum. Note, narrow telluric emission features are present in second panel at the rest wavelength of the Na I doublet feature.
statistic. This is not unreasonable for a late-F star which, according to the theoretical models, has a main sequence lifetime of $\lesssim 1$ Gyr. We then determined the evolutionary status of the host star using the results of this run to assess whether this was a reasonable assumption.

First, we examined the lithium abundance in WASP-12 as a possible age indicator. In the SARG spectrum, there is no absorption detected in the Li I line located at 6708Å. The IDS spectrum shows a broad, very shallow absorption feature at this position, however due to the lack of detection in the SARG spectrum, we suspect the feature is due to noise or blending with other absorption lines (e.g. Fe I at 6707.44Å). This lack of Li is consistent with low levels found in old open clusters, like M 67 ($\sim 4$ Gyr), for a 6300 K star (Sestito & Randich 2005), however a precise age determination cannot be derived for the star from this observation.

Next, we compare the structure and temperature of the star to the super-solar metallicity stellar evolution models of Girardi et al. (2000) to constrain the age. We use the $[\text{M/H}]=0.2$ ($Z=0.03$) tracks which are consistent with the measured metallicity of WASP-12, given the uncertainty on this parameter. Figure 6 shows a modified Hertzsprung-Russel diagram comparing the host star to the theoretical mass tracks and isochrones. Here, we plot the inverse cube root of the stellar density, $R_*/M_*^{1/3}$, in solar units versus the stellar temperature. We choose to compare the data to the models in this parameter space since the quantity, $R_*/M_*^{1/3}$, unlike $R_*$ or luminosity, is purely observational and is measured directly from the light curve. In addition, it is completely independent of the temperature determined from the spectrum.

The results of the initial MCMC run provided a measurement of the mean stellar density. We converted the density to $R_*/M_*^{1/3}$ in solar units, and generated the same property from the mass and log $g$ values in the models. We then interpolated in the $R_*/M_*^{1/3} - T_{\text{eff}}$ plane to determine the mass and age for WASP-12. We interpolated linearly along two consecutive mass tracks to generate an equal number of age points between the zero-age main sequence and the coolest point at the end of core hydrogen burning. We then interpolated between the mass tracks along equivalent evolutionary points to find the mass and age from the models that best match the stellar properties derived from the MCMC code and the synthetic spectra. According to these particular tracks, the large value for $R_*/M_*^{1/3}$ indicates the star has evolved off the zero age main sequence, but has yet to reach the shell hydrogen burning stage. It is in a position in the diagram which give it a mass, $M_*=1.33\pm0.05$ $M_\odot$ and an age of $2.0^{+0.5}_{-0.8}$ Gyr. To check the accuracy and precision of this result, we compared the star to a second set of stellar evolution models. When interpolating the $Z=0.03$ tracks by Yi et al. (2003), we find a similar result. The position of the star in the $R_*/M_*^{1/3} - T_{\text{eff}}$ gives an age of $2.4$ Gyr and a mass of $1.38$ $M_\odot$.

We investigated using the rotation period of the star which allows for constraining the age based on the expected spin-down timescale. The slow rotational period argues for an old age, however with only an upper limit on the $v\sin i$ we are unable derive an age estimate using the gyrochronology technique (Baroch 2007).

The three age-dating techniques discussed all suggest WASP-12 is several Gyr old, however the stellar evolution models provide the only definitive estimate of the age. Therefore we adopt a final age for WASP-12 of $\tau = 2\pm1$ Gyr. We have increased the uncertainty to include the error in metallicity and the systematics in the stellar evolution models.

3.2.2. Final Determination of Planet and Host Star Parameters

After determining the evolutionary status of the host star and estimating the stellar mass from the evolutionary models, we ran the MCMC code a second time. We did not impose the main sequence mass-radius prior, since the star has evolved off the zero age main sequence. Furthermore, we adopted an initial estimate for the stellar mass of $1.33$ $M_\odot$ from the comparison to the theoretical tracks.

In addition, during the radial velocity observing run, we attempted to detect the Rossiter-McLaughlin effect by taking six consecutive measurements of the target during and just after the expected transit. We see no evidence for this effect in the data which confirms a small $v\sin i$ for
WASP-12b is a unique transiting planet with the most apparent feature being the very large observed radius (1.79 \( R_J \)). The planet has a mean density only 24\% that of Jupiter, making it a member of the growing class of transiting gas giants which all have particularly large radii. Figure 7 shows the position of WASP-12b among the other published transiting planets in the mass-radius plane. The structure of these planets, including HD 209458b and WASP-1b, cannot be explained through simple, isolated planet formation models, and a great deal of recent theoretical work has gone into determining the mechanism or mechanisms causing their large sizes. It is clear that the external environment (stellar irradiation, tidal forces), the internal properties (heavy element abundance, clouds/hazes, day-night heat transfer, core mass), and the evolutionary state (age) can all affect a planet’s radius (Guillot & Showman 2002; Bodenheimer et al. 2003; Fortney et al. 2007; Burrows et al. 2007; Fortney et al. 2008; Burrows et al. 2008a,b; Jackson et al. 2008).

WASP-12b is the most heavily irradiated planet yet detected. With a host star luminosity, \( L = 3.48 L_\odot \), the planet experiences an incident flux at its substellar point of \( F_p = 9.03 \times 10^6 \text{ ergs cm}^{-2} \text{ s}^{-1} \), which is twice the stellar flux experienced by OGLE-TR-56b or OGLE-TR-132b, the next most highly irradiated planets (Torres et al. 2004; Burrows et al. 2007). This intense stellar radiation results in an equilibrium temperature, \( T_{eq} = 2516 (1-A)/F \) K, where \( A \) is the fraction of absorbed flux and \( F \) is the fraction of the planet’s surface that emits at \( T_{eq} \). Although Jupiter has an absorbing fraction, \( A = 0.28 \) (Taylor 1965), existing evidence suggests hot Jupiters have much lower albedos. For example, high precision optical photometry of HD 209458b gives an geometric albedo of only 4\% (Rowe et al. 2007).

It is clear from the detailed modeling of hot Jupiters (Bodenheimer et al. 2003; Fortney et al. 2007; Burrows et al. 2007) that increased incident stellar radiation will lead to an increase in the planet radius by inhibiting its contraction. This is a function of stellar mass and age, and less mass-
Table 3: WASP-12 system parameters and 1σ error limits derived from the MCMC analysis.

| Parameter                                                  | Symbol | Value                  | Units   |
|------------------------------------------------------------|--------|------------------------|---------|
| Transit epoch (BJD)                                        | $T_0$  | 2454508.9761$^{+0.0002}_{-0.0002}$ | days    |
| Orbital period                                             | $P$    | 1.091423$^{+0.000003}_{-0.000003}$ | days    |
| Planet/star area ratio                                     | $(R_p/R_*)^2$ | 0.0138$^{+0.0002}_{-0.0002}$ |         |
| Transit duration                                           | $t_T$  | 0.122$^{+0.001}_{-0.001}$   | days    |
| Impact parameter                                           | $b$    | 0.36$^{+0.05}_{-0.06}$      | $R_*$   |
| Stellar reflex velocity                                    | $K_1$  | 0.226$^{+0.004}_{-0.004}$   | km s$^{-1}$ |
| Centre-of-mass velocity                                    | $\gamma$ | 19.0845$^{+0.0002}_{-0.0002}$ | km s$^{-1}$ |
| Orbital semimajor axis                                     | $a$    | 0.0229$^{+0.0008}_{-0.0008}$ | AU      |
| Orbital inclination                                        | $I$    | 83.1$^{+1.4}_{-1.1}$        | degrees |
| Orbital eccentricity                                       | $e$    | 0.049$^{+0.015}_{-0.015}$   |         |
| Longitude of periastron                                    | $\omega$ | $-74^{+13}_{-10}$          | deg     |
| Stellar mass                                               | $M_*$  | 1.35$^{+0.14}_{-0.14}$      | $M_\odot$ |
| Stellar radius                                             | $R_*$  | 1.57$^{+0.07}_{-0.07}$      | $R_\odot$ |
| Stellar surface gravity                                    | log $g_*$ | 4.17$^{+0.03}_{-0.03}$   | [cgs]   |
| Stellar density                                            | $\rho_*$ | 0.35$^{+0.03}_{-0.03}$ | $\rho_\odot$ |
| Planet radius                                              | $R_p$  | 1.79$^{+0.09}_{-0.09}$      | $R_J$   |
| Planet mass                                                | $M_p$  | 1.41$^{+0.10}_{-0.10}$      | $M_J$   |
| Planetary surface gravity                                  | log $g_p$ | 2.99$^{+0.03}_{-0.03}$ | [cgs]   |
| Planet density                                             | $\rho_p$ | 0.24$^{+0.03}_{-0.02}$ | $\rho_J$ |
| Planet temperature ($A = 0,F=1$)                          | $T_{eq}$ | 2516$^{+36}_{-36}$         | K       |
Fig. 6.— $R_*/M_*^{1/3}$ in solar units versus effective temperature. WASP-12 is the large solid circle. Evolutionary mass tracks (solid lines with adjacent numbers labelling the mass of that line) and isochrones (100 Myr (solid), 1 Gyr (dashed), 2.0 Gyr (dotted), 5.0 Gyr (dot-dashed) from Girardi et al. (2000) for Z=0.03 are plotted for comparison to the WASP-12 parameters.

Fig. 7.— Mass versus Radius of all transiting planets which have published masses and radii. The data were obtained from the exoplanet encyclopedia (http://exoplanet.eu/). WASP-12b is the solid black circle. Lines of constant planet density are overplotted (dotted) in units of Jupiter density.

Evolutionary mass tracks are more affected by the star’s radiation in this regard. The extremely irradiated case of the relatively massive WASP-12b planet ($M_p=1.41 \, M_J$) at an age of $\sim 2$ Gyr is outside the range of situations presented in these papers, however, Fortney et al. (2007) give a radius of 1.24 R$_J$ for an object similar to WASP-12b (1 Gyr old, 1.46 M$_J$), but at a distance of 0.02 AU from a solar luminosity star. In the context of the models, the incident radiation from WASP-12 would be equivalent to putting this simulated planet at a distance of $\sim 0.01$ AU from a solar luminosity star. Despite WASP-12b being more intensely irradiated than the simulated planet of the same age and mass, it is difficult to see how stellar irradiation alone could result in the observed radius of $\rho_{pl} = 1.79 \, R_J$ (or even the absolute minimum radius of $\rho_{pl_{min}} = 1.63 \, R_J$) in a planet as massive as WASP-12b.

Burrows et al. (2007) show how enhancing the atmospheric opacities of extrasolar planets also results in increased radii by maintaining the heat and entropy stored in the cores over longer timescales. In their model, metallicity is used as a proxy for atmospheric heavy element abundance and thus opacity. Employing an abundance of 10× solar allows the authors to fit the radii of the largest planets without adding any additional internal heat sources. It is very likely that WASP-12b has a super-solar atmospheric heavy element abundance, given the super-solar metallicity of the host star. Furthermore, according to the models of Fortney et al. (2008), WASP-12b should be in the class of highly irradiated, hot planets (pM class) in which high-altitude molecular hazes of TiO and VO (condensation temperature, $T=1670$ K) absorb strongly at optical wavelengths resulting in larger radii. For WASP-12, measuring the primary and secondary eclipse depths as a function of wavelength and obtaining precise out-of-eclipse photometry will allow for investigating the presence of a high altitude absorbing population in the planet’s atmosphere.

Although Burrows et al. (2007) do not calculate a model specifically for WASP-12b, they are able to reproduce a 1.30 R$_J$, 1.29 M$_J$, 2.5 Gyr old planet (OGLE-TR-56b). It will be interesting to see if a complete modelling of the extreme environmental conditions of WASP-12b including stellar irradiation, increased heavy element abundance,
and high altitude hazes can produce a sufficiently large planet radius to match the observed value.

If WASP-12b’s large radius cannot be explained by increasing the atmospheric opacity or other atmospheric phenomena, an additional source of internal energy will be required to explain the observations. Dissipation of tidal energy is a possible contributor. The timescale for circularization of the WASP-12b orbit is most likely very short, but the best model fit to the observed radial velocity and light curves produces a non-zero eccentricity of $e = 0.049^{+0.015}_{-0.015}$. Using the formalism for the circularization timescale taken originally from Goldreich & Soter (1966) and provided in Bodenheimer et al. (2003), we find

$$\tau_{\text{circ}} = \frac{3.5 Q_P}{10^6} \text{ Myr}$$

which is much shorter than the 2 Gyr age of WASP-12, when $Q_P$ the tidal dissipation constant for the planet, is given the nominal value of $10^6$.

The non-zero eccentricity detection is barely a 3σ result, however, if after further observations, the detection persists, either the eccentricity must be continuously pumped by an outer planet or WASP12b’s tidal dissipation constant must be significantly larger than the typically adopted value ($10^6$). Since, the presence of an additional planet should be detectable via long term radial velocity monitoring, these two scenarios are distinguishable and thus this system might allow detailed constraints to be placed on $Q_P$, an important, but difficult to measure, parameter. Additionally, if an second planet is causing a non-zero eccentricity, the amount of internal tidal heating that must be dissipated is of order $5 \times 10^{28} \frac{Q_P}{10^6}$ ergs s$^{-1}$. This is a large amount of energy (2 orders of magnitude greater than what is calculated by Bodenheimer et al. [2003] for HD 209458b) which would have a significant effect on the radius of the planet.

WASP-12b is the hottest and largest transiting exoplanet yet detected. It has a mass, $M_{\text{pl}}=1.41$ M$_J$, radius, $R_{\text{pl}}=1.79$ R$_J$, and equilibrium planet temperature, $T_{\text{eq}}=2516$ K. The planet orbits a bright late-F star with a temperature, $T_{\text{eff}}=6300$ K and radius, $R_{\ast}=1.57$ R$_\odot$. The host star has significantly enhanced metallicity over solar, is evolving off the zero age main sequence, and has an age of $\sim 2$ Gyr. Additional follow-up observations of this exciting planet will address some of the most pressing questions in exoplanet research, in particular what mechanism or mechanisms are causing the large observed radii of some hot Jupiters and what effect does the stellar irradiation and stellar metallicity have on the atmospheric and structural properties of close-in gas giant planets.

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