

Orbital and evolutionary constraints on the planet hosting binary GJ 86 from the *Hubble Space Telescope*

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ABSTRACT

This paper presents new observations of the planet-hosting, visual binary GJ 86 (HR 637) using the *Hubble Space Telescope*. Ultraviolet and optical imaging with WFC3 confirms the stellar companion is a degenerate star and indicates the binary semimajor axis is larger than previous estimates, with $a \gtrsim 28$ au. Optical STIS spectroscopy of the secondary reveals a helium-rich white dwarf with C₂ absorption bands and $T_{\text{eff}} = 8180$ K, thus making the binary system rather similar to Procyon. Based on the 10.8 pc distance, the companion has $0.59 M_{\odot}$ and descended from a main-sequence A star of $1.9 M_{\odot}$ with an original orbital separation $a \gtrsim 14$ au. If the giant planet is coplanar with the binary, the mass of GJ 86Ab is between 4.4 and $4.7 M_{\text{Jup}}$.

The similarity of GJ 86 and Procyon prompted a re-analysis of the white dwarf in the latter system, with the tentative conclusion that Procyon hosts a planetesimal population. The periastron distance in Procyon is 20 per cent smaller than in α Cen AB, but the metal-enriched atmosphere of Procyon B indicates that the planet formation process minimally attained 25 km bodies, if not small planets as in α Cen.

Key words: binaries: visual – stars: individual: GJ 86A – stars: individual: GJ 86B – planetary systems – white dwarfs.

1 INTRODUCTION

About 20 per cent of known extrasolar planets orbit one component of a stellar binary (Haghighipour 2006; Raghavan et al. 2006). Both observation and theory indicate that the majority of these planets in binaries are similar to those orbiting single stars, owing to the wide ($a > 100$ au) stellar separations (Haghighipour 2006; Desidera & Barbieri 2007). However, there are a growing number of systems which present a major challenge to planet-formation modellers, because their *giant* planets orbit one component within closer binary systems. In order of discovery, these planetary systems are GJ 86 (HR 637, HD 13445) (Queloz et al. 2000), γ Cephei (Hatzes et al. 2003), HD 41004 (Zucker et al. 2004), HD 196885 (Correia et al.

2008) and HD 17605 (Mutterspaugh et al. 2010). All five of these binaries are thought to have $a \lesssim 30$ au and a giant planet orbiting the primary star. However, only in GJ 86 is the stellar secondary a white dwarf rather than a second main-sequence star, and the Jovian planet thus orbits the originally *less* massive component. Furthermore, the initial binary separation was smaller, making GJ 86 a challenging environment in which to form planets.

Our view of planet formation in binaries has changed significantly in the past 17 yr. Simulations of binary stars with $a < 40$ au failed to retain sufficient circumstellar material to form planets around one star, and thus precluded planet birth by either the core accretion or disc-instability mechanisms (Artymowicz & Lubow 1994; Nelson 2000; see Prato & Weinberger 2010 for a detailed review). Yet observers have imaged favourable planet-forming environments around the components of close binary stars, implying planet formation in these systems may be as common as around single stars (Mathieu 1994; Akeson, Koerner & Jensen 1998). For example, the two well-separated discs in the binary system L1551

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(Rodriguez et al. 1998) indicate that, despite disc truncation, it is still possible for both components to retain a significant amount of their original circumstellar material ($0.03\text{--}0.06 M_{\odot}$) in discs with considerable radii ($r \approx 10$ au). These disc masses are comparable to the minimum-mass model of the primordial solar nebula (Weidenschilling 1977; Hayashi 1981) suggesting that planet formation in these environments may proceed as in discs around single stars.

The Jovian planet¹ orbiting GJ 86A (K0V) was discovered via precision radial velocity monitoring (Queloz et al. 2000), revealing a 15.8-d orbit (0.11 au separation) with $m \sin i = 4 M_{\text{Jup}}$. At the time of discovery, an additional long-term radial velocity drift was reported, suggesting the presence of a more distant, unseen stellar companion. Subsequently, the distant companion was directly detected at a projected separation of 1.7 arcsec, but 9 mag fainter than the primary in the *K* band (Els et al. 2001). The companion, GJ 86B, was later imaged by Mugrauer & Neuhäuser (2005) and Lagrange et al. (2006) whose data clearly reveal orbital motion; between 2000 and 2005 the angular separation of the pair changed by 0.25 arcsec and the position angle changed by 17° . GJ 86B cannot be a low-mass star or brown dwarf: a substellar mass cannot be reconciled with the observed radial velocity drift of GJ 86A, and follow-up methane-band photometry showed GJ 86B to have a near-infrared colour index near zero. Moreover, *K*-band spectroscopy of GJ 86B reveals an essentially Rayleigh–Jeans continuum source. Thus, GJ 86B can only be a white dwarf (Mugrauer & Neuhäuser 2005; Lagrange et al. 2006).

In order to ideally constrain the formation and evolution of the giant planet orbiting GJ 86A, it is necessary to obtain the orbit and component masses of the binary system. The 3300:1 contrast ratio between components in the infrared makes this difficult but possible with adaptive optics, yet white dwarfs do not exhibit spectral features in this wavelength region. Thus an optical study of GJ 86B is necessary and a *Hubble Space Telescope* (*HST*) program was initiated to achieve this goal. Section 2 describes the imaging and spectroscopic observations, while Section 3 describes the atmospheric modelling, derivation of current (and progenitor) stellar parameters and binary orbit constraints. New static limits on the GJ 86 planetary system are calculated based on the *HST* observations and possible similarities with the Procyon system are discussed in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

Because of orbital motion observed between 2000 and 2005 (Mugrauer & Neuhäuser 2005; Lagrange et al. 2006), it was expected that precise spatial offsets might be necessary for proper placement of the faint companion within the spectroscopic aperture. Thus, imaging was executed for both photometric and astrometric purposes, prior to spectroscopy.

2.1 WFC3 imaging

GJ 86 was imaged on 2012 March 31 using the Wide Field Camera 3 (WFC3) in the UVIS channel with a 512×512 (UVIS2-C512C-SUB) subarray. The imaging sequence took place over a single orbit and began with a series of 1 s exposures in the F225W filter. In this short exposure time, the flux from the $V = 6.2$ mag, $T_{\text{eff}} \approx 5200$ K primary was expected to leave an unsaturated, linear response on

Table 1. *HST* cycle 19 observations of GJ 86B.

Instrument	UT date	Filter/grating	Exposures (s)
WFC3 UVIS	2012 March 31	F225W	1.0×16
		F225W	20.0×4
		F275W	10.0×4
		F336W	5.0×4
		F390W	4.0×4
		F438W	4.0×4
		F555W	2.0×4
		F625W	2.0×4
STIS CCD	2012 May 29	F814W	30.0×4
		G430L	100.0×3
		G430M	600.0×4
		G750M	400.0×3

the CCD. This sequence employed the default UVIS dither pattern with four points in a parallelogram, and was repeated four times for a total of 16 exposures. Both primary and secondary star were well detected in this first set of exposures, and in the linear response regime with high signal-to-noise ratio ($S/N > 500$). This set of images was used to robustly measure the separation of the binary, where the secondary star was found at offset:

$$\alpha = 2.351 (2) \text{ arcsec} \quad \theta = 88^\circ 96 (4) (J2000) \quad \text{Date: 2012.2468.}$$

Immediately following the short-exposure sequence, a single dither pattern of four deeper exposures was executed in each of eight filters (see Table 1 and Fig. 1). At the phase II design stage, the brightness of the companion was poorly constrained and the longer exposures were to insure high S/N photometry [up to the limit imposed by the point spread function (PSF) wings of the primary] at all wavelengths. Fortunately, even without stray light correction, the dither-combined image sets yielded $S/N > 500$ for GJ 86B shortward of 5500 \AA , and $S/N > 200$ beyond. Thus, the relatively faint companion was mostly unaffected by the primary.

Photometry was performed on multidrizzled images produced by the Space Telescope Science Institute software and data pipeline OPUS 2012.1 and CALWF3 2.6.2. The flux of GJ 86B was measured in an $r = 7$ pixel aperture radius and corrected using the encircled energy data available in the WFC3 Instrument Handbook, version 3.0 (Dressel et al. 2010). The aperture corrections were derived by interpolating the tabular values at the effective wavelength of the best-fitting atmospheric model (see Section 3) in each bandpass, and the process was iterated until there were no significant changes in the photometry or stellar model parameters; in practice this occurred after a single repetition. The background flux of GJ 86A was subtracted by examining points opposite, in x and y on the subarray, from the bright primary. This ambient light correction resulted in flux measurement changes less than 1.2 per cent for the five filters below 5000 \AA , but rose to around 4 per cent for the three longer wavelength filters. The measured fluxes for GJ 86B are listed in Table 2.

2.2 STIS spectroscopy

Observations with the Space Telescope Imaging Spectrograph (STIS) were executed on 2012 May 29, beginning with an acquisition sequence of GJ 86A, followed by an offset and acquisition/peak-up of GJ 86B based on the WFC3 astrometry. Examination of the acquisition and peak-up images shows they were

¹ The planet is often referred to incorrectly as GJ 86b, while the correct designation is GJ 86Ab.

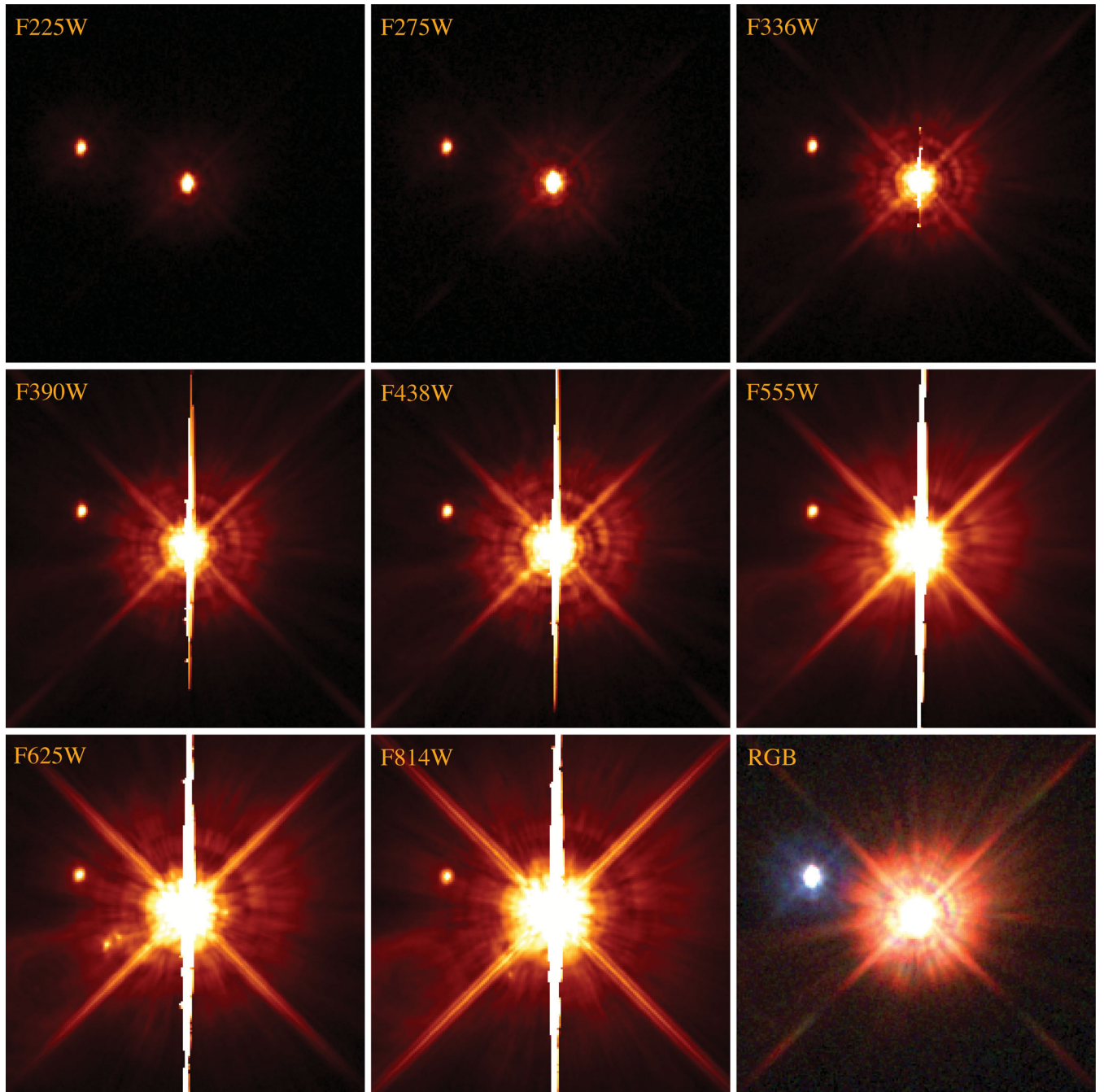


Figure 1. Images of GJ 86 in the eight specified ultraviolet and optical filters using WFC3 UVIS. The images are oriented so that upward is $17^{\circ}60'$ east of north, and each frame is 8 arcsec on a side. The bottom right-hand image is a composite RGB frame using the F225W (blue), F275W (green) and F336W (red) filters. A series of short exposures at F225W was obtained with an unsaturated primary, and these data were used for the relative astrometry of the pair.

successful. Spectroscopy was performed with the G430L, G430M, and G750M gratings as detailed in Table 1, using default STIS dither patterns along the slit, and achieving average resolutions of 6.8, 0.7, and 1.4 \AA , respectively.

The individual spectral images were first shifted on to a common frame as indicated by the image header astrometry and using integer pixel shifts. Next, the shifted images were combined into a single 2D frame using `MSCOMBINE` in the `IRAF STSDAS` software package. Prior to this step, the spectral images contained a significant number of bad pixels and cosmic rays, especially in the G430M observations. Rejection of these unwanted pixels was performed using `CCDCLIP`

at 4σ , although this could not completely remove the accumulated artefacts.

Fig. 2 shows the final, combined spectral images for each of the grating settings. Although stray light from the primary is apparent in all the images, and most readily seen in the red, the signal from GJ 86B was essentially unaffected. The contrast between the peak signals from the science target and the primary diffraction spikes was 17:1 at the lowest in the G750M observations, and at least twice as high in the region of the science spectrum.

Lastly, 1D spectra were extracted using `X1D`, and appropriate sky subtraction to correct for the relatively mild background. The

Table 2. Flux densities and effective wavelengths for GJ 86B.^a

Filter	λ_{eff}^b (Å)	$F_{\lambda}/10^{-14}$ (erg s ⁻¹ cm ⁻² Å ⁻¹)	$F_{\nu}/10^{-26}$ (erg s ⁻¹ cm ⁻² Hz ⁻¹)
F225W	2385	3.49	6.62
F275W	2722	4.04	9.99
F336W	3355	3.93	14.76
F390W	3908	3.40	17.34
F438W	4315	3.02	18.75
F555W	5237	2.18	19.91
F625W	6183	1.56	19.87
F814W	7899	0.80	16.74

^aThe flux of GJ 86A was measured to be 31.4 mJy in F225W.^bEffective wavelengths were derived by convolving the adopted stellar model in F_{λ} with the WFC3 filter transmission curves.

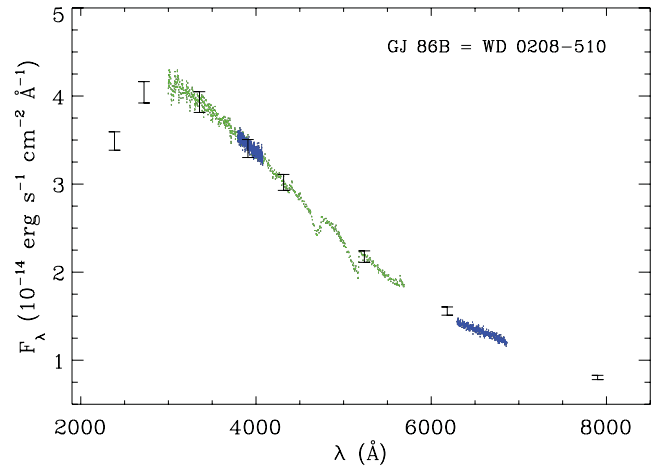
flux-calibrated and normalized STIS spectra are displayed in Figs 3 and 4. The S/N per pixel was determined from continuum regions within each of the spectra to be close to 85, 88, and 53 in the G430L, G430M, and G750M gratings, respectively.

3 STELLAR AND BINARY PARAMETERS

The upper spectrum shown in Fig. 4 displays the distinctive and broad C₂ Swan bands, indicating that GJ 86B has a DQ spectral classification. This class of white dwarfs is characterized by helium-dominated atmospheres with trace carbon, likely dredged from the core (Pelletier et al. 1986). Neither Ca II K nor H α were detected in the relatively deep and higher resolution G430M and G750M spectra. Following convention the star has the white dwarf designation WD 0208–510 (McCook & Sion 1999).

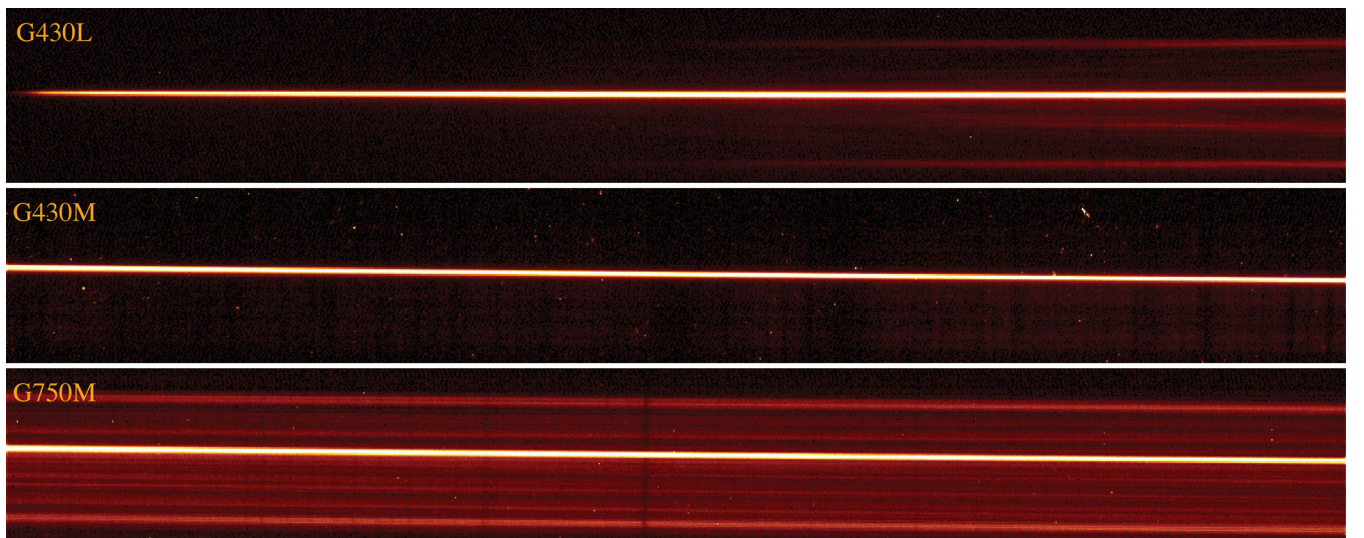
3.1 Atmospheric modelling

Stellar parameters for GJ 86B were derived in two ways, using model atmosphere grids appropriate for DQ white dwarfs (see Dufour, Bergeron & Fontaine 2005, for details on the models and fitting techniques). First, the effective temperature and solid angle were

**Figure 3.** Flux-calibrated WFC3 photometry and STIS spectra of GJ 86B for each of the configurations specified in Table 1. Fig. 4 plots the spectra in greater detail.

estimated from fitting the broad baseline WFC3 photometry. These parameters were then combined with the *Hipparcos* parallax of 92.74 mas (Perryman et al. 1997; van Leeuwen 2007) to determine the stellar radius, which was then converted into mass using theoretical mass–radius relationships (Fontaine, Brassard & Bergeron 2001). However, the shape of the energy distribution – and thus the derived effective temperature – is slightly sensitive to the amount of photospheric carbon. Model fits to the C₂ Swan bands in the G430L STIS spectrum were used to measure the carbon abundance, with T_{eff} and $\log g$ fixed at the values obtained from the WFC3 photometry. The effective temperature and solid angle were re-derived using C/He fixed to the spectroscopic value. This procedure was iterated until all parameters converged, with a good fit obtained at $T_{\text{eff}} = 8420 \pm 90$ K, $\log(\text{C}/\text{He}) = -4.58 \pm 0.15$.

Secondly, because the STIS data are flux calibrated with a high degree of confidence, the effective temperature and carbon abundance can be simultaneously obtained from the G430L spectrum

**Figure 2.** Combined-frame STIS CCD spectral images of GJ 86B taken in three gratings, with wavelength increasing to the right. The ambient light of the primary is relatively mild, even in red light. Despite rejection routines that drastically reduced the number of cosmic rays, hot and cold pixels present in the single exposures, some artefacts remain in the combined 2D images, especially at the shortest wavelength setting.

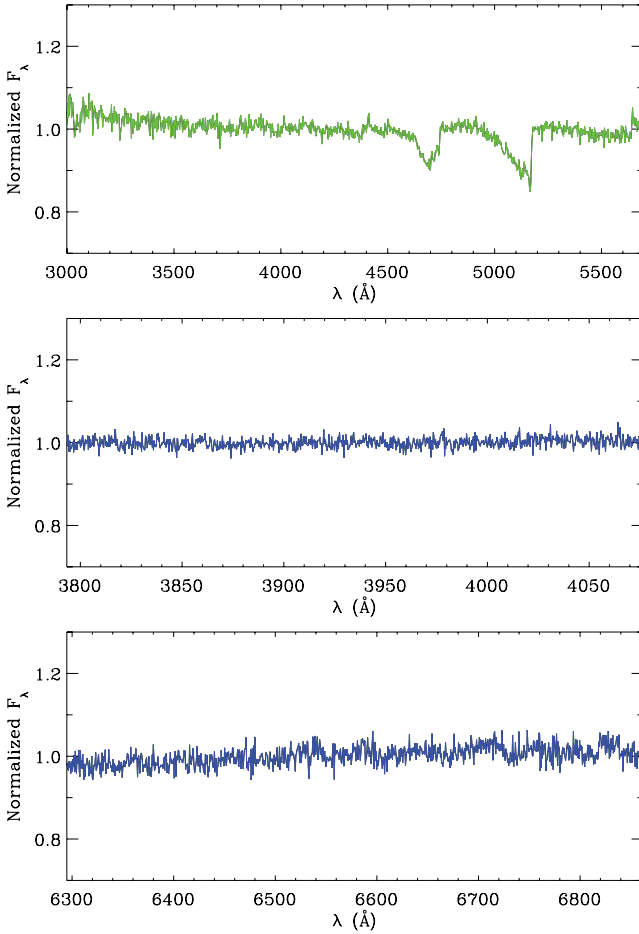


Figure 4. From top to bottom are normalized STIS spectra of GJ 86B obtained with the G430L, G430M, and G750M gratings. The only detected spectral features are the C₂ Swan bands. Upper limits on calcium and hydrogen were derived from the Ca II K and H α regions (Table 3).

alone, yielding $T_{\text{eff}} = 8145 \pm 180$ K, $\log(\text{C}/\text{He}) = -4.82 \pm 0.15$. The difference in resulting model parameters is significant and most likely caused by the two shortest wavelength fluxes. Indeed, the F225W and F275W bandpasses span a region influenced by at least one strong C I line which models tend to overpredict (in the core or wings). An example of this was observed by Provencal et al. (2002) in the STIS ultraviolet spectrum of Procyon B, where the strength of the 2478 Å line is much weaker (by nearly a factor of 30 in C/He) than predicted by models. The model shortcomings are understood to be a consequence of the high-density environments in cool helium-rich white dwarf photospheres; the classical Van der Waal broadening treatment within the impact approximation, traditionally used in DQ model atmospheres, is not appropriate for these lines (Koester, Weidemann & Zeidler 1982).

If one ignores the two ultraviolet fluxes affected by these strong C I lines, and uses the remaining six WFC3 photometric data points, then $T_{\text{eff}} = 8210 \pm 180$ K, $\log(\text{C}/\text{He}) = -4.76 \pm 0.15$ is obtained, in agreement with the parameters from fitting the spectrum alone. For all stellar and evolutionary parameters, the weighted average of the photometric (ignoring F225W and F275W) and spectroscopic effective temperatures, and the non-weighted average of the carbon abundances are thus adopted and listed in Table 3 ($T_{\text{eff}} = 8180 \pm 120$ K and $\log(\text{C}/\text{He}) = -4.8 \pm 0.2$). Upper limit hydrogen and calcium abundances were also derived and are listed in Table 3,

Table 3. Current and progenitor stellar parameters for GJ 86AB.

GJ 86B/WD 0208–510	
White dwarf remnant:	
SpT	DQ6
V_{eff} (mag)	13.2
T_{eff} (K)	8180 ± 120
$\log g$ (cm s^{-2})	8.02 ± 0.02
Mass (M_{\odot})	0.59 ± 0.01
Radius (R_{\odot})	0.01245 ± 0.0015
Cooling age (Gyr)	1.25 ± 0.05
$\log(\text{C}/\text{He})$	-4.8 ± 0.2
$\log(\text{H}/\text{He})$	< -4.3
$\log(\text{Ca}/\text{He})$	< -11.8
Main-sequence progenitor:	
SpT	A5 V
Mass (M_{\odot})	1.9 ± 0.1
Lifetime (Gyr)	1.4 ± 0.2
GJ 86A/HR 637/HD 13445	
SpT	K0 V
V (mag)	6.1
T_{eff} (K)	5200
Mass (M_{\odot})	0.80
Age (Gyr)	2.5

Note. Parameters listed for GJ 86A are values representative of those found in the literature (Flynn & Morell 1997; Ribas et al. 2003; Saffe, Gómez & Chavero 2005; Valenti & Fischer 2005; Mamajek & Hillenbrand 2008; van Belle & von Braun 2009; Ghezzi et al. 2010).

while Fig. 5 shows the best-fitting model compared to the photometry and G430L spectrum. All the derived stellar parameters are listed in Table 3.

3.2 Current binary orbit

The epoch 2012.2 WFC3 imaging provides a new point along the binary orbit of GJ 86, and is shown in Fig. 6 together with previous astrometric measurements (Els et al. 2001; Lagrange et al. 2006). Unfortunately, one quarter of the full orbit has not yet been observed, and hence the orbital parameters can only be loosely constrained. For all orbital calculations, $M_A = 0.8 M_{\odot}$ and $M_B = 0.6 M_{\odot}$ are adopted for simplicity; the actual component masses are not better constrained at present.

Using the new astrometric datum, a statistical analysis of orbits that fit the observations was performed. A Monte Carlo simulation of 10 000 orbital solutions was created with periods from 20 to 500 yr, eccentricities from 0.00 to 0.99 and with time of periastron passage from 1800 to 2200. From these solutions, the 100 orbits with the best χ^2 values, and with total masses within the limited range $M_{\text{tot}} = 1.4 \pm 0.1 M_{\odot}$ were selected. These orbits are plotted in Fig. 6, and the resulting range in orbital parameters is listed in Table 4. As can be seen, only the system inclination is significantly constrained at present. The solutions with low eccentricities tend to have relatively short orbital periods, whereas the longer period solutions require high eccentricities. Notably, the orbital solution with the shortest period yields a semimajor axis $a = 27.8$ au with eccentricity $e = 0.10$, and is significantly larger than the representative solution with $a = 18.4$ au adopted by Lagrange et al. (2006).

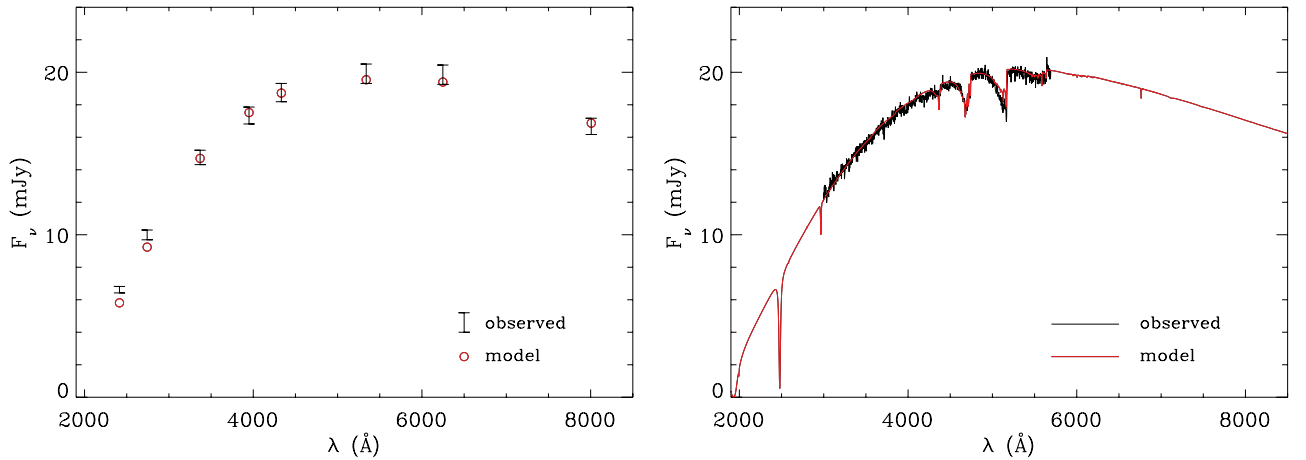


Figure 5. Comparison between the observed and modelled stellar fluxes. In the left-hand panel, the model fluxes agree well with the WFC3 photometry in all bandpasses except F225W and F275W (see Section 3.1). In the right-hand panel the model spectrum reproduces both the optical continuum and C_2 bands in the STIS G430L data, but indicates a strong C_1 2478 Å feature that underpredicts the stellar flux in the two ultraviolet filters. All spectral features are due to atomic or molecular carbon.

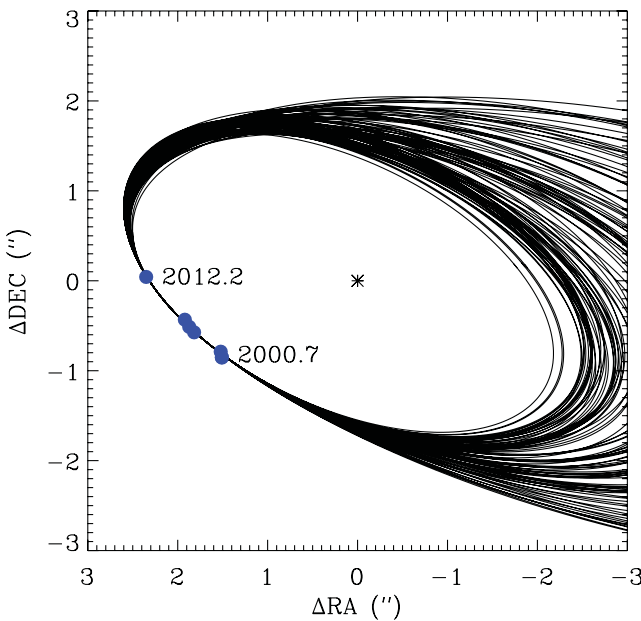


Figure 6. The blue data points are the astrometric offsets determined here using WFC3 (leftmost point), together with those reported by Lagrange et al. (2006) and Els et al. (2001). An initial sample of 10 000 orbital solutions was generated through a Monte Carlo search, and overplotted in black are the 100 orbits with the best χ^2 values, within the restricted mass range $M_{\text{tot}} = 1.4 \pm 0.1 M_{\odot}$.

4 BINARY AND PLANETARY EVOLUTION

4.1 Total system age

The white dwarf cooling age places a firm lower limit of 1.3 Gyr on the lifetime of the system (Fontaine et al. 2001). For the total age, one must add the hydrogen-burning lifetime of the progenitor, which should be in the range 1.2–1.6 Gyr for stars of mass 1.8–2.0 M_{\odot} . Thus, the evolved companion suggests a total system age of 2.65 ± 0.25 Gyr. Age estimates for the primary include 2.0–2.9 Gyr (Saffe et al. 2005) and 2.4 Gyr (Mamajek & Hillenbrand 2008) based on activity–age relations, and these broadly agree with that derived for the secondary. Mamajek & Hillenbrand (2008) prefer an age

Table 4. Orbital constraints from Monte Carlo simulations.

Parameter	Range
P	120–481 yr
T_0	1933–2067
e	0.00–0.61
a	2.57–6.47 arcsec
	27.8–69.8 au
i	114°7′–122°6′
Ω	63°7′–76°1′
ω	0°–358°

Note. The upper range of periods and semimajor axes result from the simulation input $P_{\text{max}} = 500$ yr, but these orbits require high eccentricities $e > 0.5$ and are thus less likely.

of 3.7 Gyr based on activity–rotation–age metrics, but this value is significantly older than expected for the total lifetime of the white dwarf and its progenitor.

4.2 The main-sequence progenitor system

To constrain formation scenarios for the giant planet orbiting GJ 86A, the binary orbit and component masses when both stars were on the main sequence are needed. Using initial-to-final mass relations with some empirical constraints at the low-mass end of progenitor and remnant masses (Kalirai et al. 2008; Williams, Bolte & Koester 2009), GJ 86B likely descended from a main-sequence, A-type star with a mass near 1.9 M_{\odot} . With both stars on the main sequence, the semimajor axis of the binary was smaller by a factor (Jeans 1924)

$$\frac{a_0}{a} = \frac{M_B + M_A}{M_{B_0} + M_{A_0}}. \quad (1)$$

This ratio is not very sensitive to the range of allowed masses, and yields $a_0 = 0.52a$ for $M_A = 0.80 M_{\odot}$, $M_B = 0.59 M_{\odot}$, $M_{B_0} = 1.86 M_{\odot}$. A canonical mass value has been assumed for the primary, but is consistent with isochrones and various literature estimates (Flynn & Morell 1997; Ribas et al. 2003; Valenti &

Fischer 2005; van Belle & von Braun 2009). From the current binary orbit simulations, a lower limit on the initial semimajor axis is obtained $a_0 \geq 14.5$ au. Even at this lower limit, the 0.11 au planetary orbit of GJ 86Ab is stable for binary eccentricities $e < 0.9$ (Rabl & Dvorak 1988; Holman & Wiegert 1999).

4.3 Planetesimals in GJ 86

Although the class of detached binary stars with a white dwarf and a main-sequence component of spectral type K or earlier are referred to as Sirius-type binaries (Holberg et al. 2008), GJ 86 is also notably *Procyon-like*. Table 5 lists the atmospheric and stellar parameters for these two white dwarf companion systems, demonstrating their broad similarities.

Because GJ 86 is known to host a planetary system, with at least one giant planet orbiting the primary, it may also support a planetesimal population. These surviving minor bodies could be gravitationally perturbed into close encounters with the white dwarf, where they would be tidally shredded and eventually accreted, polluting the atmosphere with heavy elements (Jura 2003), as observed at nearly 30 single white dwarfs (Debes et al. 2012; Farihi et al. 2012; Gänsicke et al. 2012; Kilic et al. 2012). In a binary such as GJ 86, stable planetesimal belts can persist as circumstellar rings at either star or a circumbinary disc.

One region that remains stable over both the current and former binary configurations and $e < 0.1$ is within roughly 3 au of the K star primary. Stable circumstellar regions for the white dwarf are complicated by competing processes: while the region within 2 au will be depleted of small bodies by direct engulfment and tides during the giant phases (Mustill & Villaver 2012), surviving objects will have their orbit expanded due to mass loss, by a factor of $M_{B0}/M_B \approx 3.2$. However, the critical radius for stability also increases due to mass loss, but by a factor smaller than $(M_B + M_A)/(M_{B0} + M_A) \approx 1.9$, and therefore a narrow range of stable, planetesimal orbits are possible for the white dwarf if $a \gtrsim 30$ au currently. It is worth noting that these calculations are purely static, and thus ignore the dynamic effects of mass loss which may have significant impact on stable orbits (Veras et al. 2011; Veras & Tout 2012). Circumbinary orbits beyond 80 au are also stable in the current and former binary configurations for $a \approx 30$ au and $e < 0.1$.

Thus, one of the science goals of the *HST* observing program was to search for evidence of planetesimals in this system, via atmospheric metal pollution in the white dwarf. As discussed in Section 2.2, calcium absorption was not detected in the STIS data, and a strict upper limit of $\log(\text{Ca}/\text{He}) < -11.8$ was derived for GJ 86B.

This corresponds to $M_{\text{Ca}} < 3.2 \times 10^{17}$ g in the stellar convection zone, or an upper limit to the total accreted heavy element mass of $M_Z \lesssim 2.0 \times 10^{19}$ g for material that is 1.6 per cent calcium by mass as in the bulk Earth (Allègre et al. 1995). Because the Ca II K line is the most sensitive tracer of metal pollution at optical wavelengths for white dwarfs of this effective temperature (Zuckerman et al. 2003; Koester et al. 2005), this large cometary-sized mass is the strongest possible limit to the observable planetesimal population.

4.4 A failed planetary system at Procyon?

Interestingly, and also using STIS, Provencal et al. (2002) found that Procyon B exhibits a strong Mg II resonance line at 2800 Å, a few Fe lines in the near-ultraviolet and Ca II H&K absorption in the optical. While Procyon is not known to host any planets or planetesimal debris (via precision radial velocity, transits, astrometry, direct imaging or infrared excess), the white dwarf is externally polluted with at least three heavy elements that could have originated in a minor planetary body (Farihi et al. 2010). Using the published magnesium abundance, Procyon B has accreted at least $M_{\text{Mg}} = 5.1 \times 10^{18}$ g within the past few 10^7 yr, where 2.8 Myr is a single sinking time-scale for this element at the stellar effective temperature (Koester 2009). For material with a chondritic or Earth-like elemental abundance, this is equivalent to a total accreted heavy element mass of at least $3\text{--}6 \times 10^{19}$ g (Allègre et al. 1995; Lodders & Fegley 1998), and equivalent to a 25–35 km diameter object for typical asteroid densities.

Other possible sources for the atmospheric metals are the interstellar medium (ISM), or the stellar wind from Procyon A (Provencal et al. 2002). In both of these cases the accreted matter would have solar abundances ($\log(\text{Mg}/\text{H}) = -4.45$, $\log(\text{Mg}/\text{He}) = -3.35$; Lodders 2003) and imply time-averaged accretion rates of $\dot{M}_{\text{H}} = 8.0 \times 10^8$ g s⁻¹ and $\dot{M}_{\text{He}} = 2.6 \times 10^8$ g s⁻¹. If the heavy elements have been continually captured from Procyon A, then hydrogen and helium should have accumulated in the white dwarf atmosphere over its 1.4 Gyr cooling age (Fontaine et al. 2001). During this period 3.6×10^{25} g of hydrogen and 1.1×10^{25} g of helium will have been added to the 2.1×10^{28} g helium convection zone, yielding a current abundance $\log(\text{H}/\text{He}) = -2.2$. However, the upper limit derived from the lack of H α absorption is $\log(\text{H}/\text{He}) < -3.7$ and inconsistent with stellar wind accretion.

If one ignores the issue of hydrogen accumulation, the mass-loss rate from Procyon A that is necessary to supply the magnesium in the white dwarf at the observed time-averaged rate is $1.8 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ for a Bondi–Hoyle accretion flow (Debes 2006) and $9.1 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ for gravitational (Eddington) accretion. These mass-loss rates are between 5 and 7 *orders of magnitude* larger than that measured for the Sun and α Cen (Withbroe 1989; Wood et al. 2001). Therefore, wind capture can be ruled out with confidence. Similar arguments can be used to discount the accretion of interstellar matter. First, hydrogen accumulates whereas metals sink, and thus the hydrogen-deficient atmosphere of Procyon B is at odds with the accretion of solar abundance material for more than 2 per cent of its cooling lifetime. Secondly, molecular cloud densities are required to account for the observed metals (Farihi et al. 2010), but Procyon has been moving within the local, $r \sim 100$ pc, ISM-poor bubble (Redfield & Linsky 2008) for at least 2.6 Myr.

The remaining possibility is the accretion of one or more planetesimals. Accounting for both the current and former binary configurations, stable orbital regions at Procyon can be either circumbinary beyond 55.4 au or circumpriary within 2.3 au (Holman & Wiegert

Table 5. Comparison of GJ 86B and Procyon B.

Parameter	GJ 86B	Procyon B ^a
SpT	DQ6.2	DQZ6.5
T_{eff} (K)	8180	7740
Mass (M_{\odot})	0.59	0.60
$\log(\text{H}/\text{He})$	< -4.3	< -3.7
$\log(\text{C}/\text{He})$	-4.8	-5.5
$\log(\text{Mg}/\text{He})^b$...	-10.4
$\log(\text{Ca}/\text{He})$	< -11.8	-11.8
Primary SpT	K0 V	F5 IV
a (au)	≥ 28	15.2
e	...	0.41

^aAtmospheric parameters from Provencal et al. (2002).

^bThe STIS spectra of GJ 86B do not cover the Mg II 2800 Å resonance lines.

1999), although bodies in the latter region would be dynamically unlikely to be perturbed towards the surface of the white dwarf. There is no circumstellar region at Procyon B that remains stable over the lifetime of the binary. Thus, a circumbinary population of planetesimals is the most likely source of the metals observed in Procyon B. Observations with *Herschel* PACS at 160 μm have not detected a far infrared excess at Procyon, and limit the fractional dust luminosity to $L/L_* < 5 \times 10^{-7}$ over the 30–300 au region (G. Kennedy, private communication). This limit is only a few times greater than the fractional dust luminosity of the Kuiper belt (Stern 1996; Booth et al. 2009), and for similar particles would result in an upper dust mass limit of roughly an Earth mass for Procyon.

On the main sequence, Procyon should have had a semimajor axis near 9 au. Even for $e = 0.1$ this implies that disc material available for planet building would be confined to within 2.0 au of Procyon A and 2.4 au of Procyon B, and thus completely within their respective snow lines. Thus, giant planet formation at either component of the Procyon system is likely precluded, and likely also for the $a > 55$ au stable circumbinary environment. Only the inner regions of Procyon A appear capable of forming small, solid planets (as in α Cen AB; Dumusque et al. 2012), that persist to the present day, assuming the binary eccentricity was not larger when both stars were on the main sequence. Thus, the Procyon system may represent a case of failed or truncated planet formation, where large planetesimals were formed but further growth was prohibited.

5 SUMMARY AND OUTLOOK

High-contrast optical imaging and low-resolution spectroscopy with *HST* have unambiguously characterized the stellar companion to the planet host star GJ 86A. The secondary is a relatively cool white dwarf with a helium-dominated atmosphere and molecular absorption bands due to trace carbon, which is almost certainly dredged from the core. Neither $H\alpha$ nor Ca II K is detected in deeper, medium-resolution spectroscopy, the latter placing modest limits on the presence of scattered planetesimal material.

The binary separation of GJ 86 has continued to increase since last observed in 2005, and the actual orbit deviates from prior estimates. While one-quarter orbit has not yet been observed, Monte Carlo simulations constrain the semimajor axis to $a \geq 27.8$ au, and the system inclination within $114.7^\circ \leq i \leq 122.6^\circ$. For planetary–binary coplanar orbits, these results imply the mass of GJ 86Ab lies between 4.4 and 4.7 M_{Jup} .

Future imaging is necessary to observe apastron and dynamically constrain the component masses. This can be done with adaptive optics in the near-infrared, but superior data will come from follow up imaging and spectroscopy with *HST* in the near-ultraviolet. In this relatively low-contrast wavelength regime, there will be narrow absorption lines from C I, and possibly Mg II which is a strong absorption feature in Procyon B. Such spectral lines can provide a baseline radial velocity and gravitational redshift for the secondary; these would more efficiently characterize the current and former binary configurations than near-infrared data.

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