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Cool Jupiters greatly outnumber their toasty siblings: occurrence rates from the Anglo-Australian Planet Search

Robert A. Wittenmyer ,[1★] Songhu Wang,[2†] Jonathan Horner,[1] R. P. Butler,[3] C. G. Tinney,[4] B. D. Carter,[1] D. J. Wright,[1] H. R. A. Jones,[5] J. Bailey ,[4] S. J. O'Toole [6,7] and Daniel Johns[8]

[1]*University of Southern Queensland, Centre for Astrophysics, USQ Toowoomba, QLD 4350, Australia*
[2]*Department of Astronomy, Yale University, 52 Hillhouse Avenue, New Haven, CT 06511, USA*
[3]*Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015-1305, USA*
[4]*School of Physics and Australian Centre for Astrobiology, University of New South Wales, Sydney 2052, Australia*
[5]*Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield, Herts AL10 9AB, UK*
[6]*Australian Astronomical Observatory, 105 Delhi Rd, North Ryde, NSW 2113, Australia*
[7]*Australian Astronomical Optics, Faculty of Science and Engineering, Macquarie University, 105 Delhi Rd, North Ryde, NSW 2113, Australia*
[8]*Department of Physical Sciences, Kutztown University, Kutztown, PA 19530, USA*

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ABSTRACT

Our understanding of planetary systems different to our own has grown dramatically in the past 30 yr. However, our efforts to ascertain the degree to which the Solar system is abnormal or unique have been hindered by the observational biases inherent to the methods that have yielded the greatest exoplanet hauls. On the basis of such surveys, one might consider our planetary system highly unusual – but the reality is that we are only now beginning to uncover the true picture. In this work, we use the full 18-yr archive of data from the Anglo-Australian Planet Search to examine the abundance of 'cool Jupiters' – analogues to the Solar system's giant planets, Jupiter and Saturn. We find that such planets are intrinsically far more common through the cosmos than their siblings, the hot Jupiters. We find that the occurrence rate of such 'cool Jupiters' is $6.73^{+2.09}_{-1.13}$ per cent, almost an order of magnitude higher than the occurrence of hot Jupiters (at $0.84^{+0.70}_{-0.20}$ per cent). We also find that the occurrence rate of giant planets is essentially constant beyond orbital distances of ∼1 au. Our results reinforce the importance of legacy radial velocity surveys for the understanding of the Solar system's place in the cosmos.

Key words: techniques: radial velocities – planets and satellites: detection – planets and satellites: gaseous planets.

1 INTRODUCTION

The story of the Exoplanet Era has been one of continual surprises. With each new discovery technique, and each new observing facility, planets have been discovered that fail to conform to our expectations of what a planetary system should look like. From the warm and hot Jupiters and pulsar planets that marked our entry to the era (e.g. Wolszczan & Frail 1992; Mayor & Queloz 1995; Wright et al. 2012), to the highly eccentric worlds found by radial velocity (RV) surveys (e.g. Jones et al. 2006; Wittenmyer et al. 2007a; Tamuz et al. 2008; Wittenmyer et al. 2017c), as more planets have been found, we have discovered that the population is far more diverse than we could have possibly imagined (see e.g. the review by Winn & Fabrycky 2015).

In one planetary system that we can study in depth, we also see a great diversity (e.g. Horner et al. 2020, *submitted*). From small, overdense planets locked in spin–orbit resonance (Mercury, e.g. Cameron, et al. 1988; Benz, et al. 2007; Chau et al. 2018) to giants with vast numbers of satellites (Jupiter and Saturn, e.g. Sheppard & Jewitt 2003; Jewitt & Haghighipour 2007; Holt et al. 2018), it is apparent that the complexity of planetary systems only increases as more information is gleaned.

Despite the fact that we are now 30 yr into the Exoplanet Era, we are only now beginning to find systems that truly resemble our own (e.g. Marcy et al. 2002; Wittenmyer et al. 2014b, 2017a; Agnew et al. 2018; Buchhave et al. 2018). When one considers the distribution of all exoplanets found to date, and compares it with the planets in the Solar system, the only two which we would have had any chance of discovering to date are the gas giants Jupiter and

★ E-mail: rob.w@usq.edu.au
† 51 Pegasi Fellow.

Saturn (Horner et al. 2020). With orbital periods of 12 and 29 yr, our two giant planets could be considered a pair of 'cool Jupiters'. With this motivation, in this work we define 'cool Jupiters' as planets with masses greater than 0.3 $M_{\rm Jup}$ and orbital periods longer than 100 d. Such planets are definitively gas giants, analogous to our own Jupiter and Saturn, and this mass boundary is compatible with the detection limits achievable by long-term RV surveys; Saturn imposes an RV signal of $K \sim 3\,\mathrm{m\,s^{-1}}$ over its 29-yr period.

As the dynamically dominant and most readily detectable planets in our Solar system, it is natural to ask whether planetary systems with architectures like our own (i.e. with the most massive planets moving on relatively distant, long-period orbits) are common, or are unusual. Answering this question will provide the first step towards a wider understanding of the uniqueness of the Solar system in the context of the wider exoplanet population, and is tied to an understanding of the frequencies of Jupiter analogues (Wittenmyer et al. 2016) and that of Earth-like planets. Given the widely discussed influence of such giant planets on the formation, evolution, and potential habitability of Earth-like planets within the same system (e.g. Raymond et al. 2006; Horner & Jones 2008, 2009, 2010, 2012; Horner et al. 2010, 2019; Grazier 2016; Raymond & Izidoro 2017; Bryan et al. 2019), the answer is clearly of wide interest.

There is, however, a problem. The vast majority of newly discovered exoplanets move on orbits that huddle close to their host stars, and precious few are found on orbits that take years or decades to complete (e.g. Kane et al. 2019; Rickman et al. 2019; Wittenmyer et al. 2019). These discovery statistics are primarily the result of the biases inherent in the predominant discovery technique – the search for transiting worlds (e.g. Perryman 2018). Both *Kepler* and *TESS*, the most successful planet discovery factories of the past decade and coming years, respectively, are heavily biased towards finding planets moving on orbits with periods measured in days and weeks, rather than years and decades (e.g. Borucki et al. 2010; Batalha et al. 2013; Rowe et al. 2014; Ricker et al. 2015; Barclay et al. 2018; Nielsen et al. 2019).

To detect planets analogous to Jupiter and Saturn, different techniques must come to the fore. Around young stars, where planets are still self-luminous from the accrued heat of their accretion, such worlds can potentially be found through direct imaging (e.g. Kalas et al. 2008; Marois et al. 2008, 2010; Lagrange et al. 2009; Sallum et al. 2015; Bowler 2016). However, that science is still very much in its infancy, and precious few worlds have been discovered to date.[1] In much the same vein, long-term studies of the astrometric motion of stars should yield a harvest of Jovian planets – with some authors predicting that the *Gaia* spacecraft could find tens of thousands of such planets in the coming decade (Perryman et al. 2014). Again, however, that science is still in its youth – with no definitively planetary objects having yet been discovered astrometrically.

Fortunately, there exists another solution. The RV surveys that launched the Exoplanet Era, three decades past, have now achieved temporal baselines and precisions sufficient to reveal planets akin to those in our own Solar system. Few such 'legacy' surveys are still operating, with the Anglo-Australian Planet Search (AAPS; e.g. Tinney et al. 2001, 2011; Wittenmyer et al. 2017a) having been brought to a close in 2014 for a total time baseline of 18 yr. The McDonald Observatory planet search is one of the last remaining legacy surveys still in regular operation, with more than 20 yr of precise RVs from the 2.7-m Harlan J. Smith Telescope (e.g. Cochran & Hatzes 1993; Wittenmyer et al. 2006). That programme continues to deliver valuable new discoveries of long-period giant planets (e.g. Robertson et al. 2012a,b; Endl et al. 2016; Blunt et al. 2019). The CORALIE survey has also been running for more than 20 yr (Queloz et al. 2000; Marmier et al. 2013; Rickman et al. 2019). Despite the untimely demise of AAPS and similar programmes, the legacy data sets they provide offer the possibility to investigate both the occurrence of cool giants and the frequency with which they occur in pairs.

In this paper, we use the complete AAPS data set to explore the occurrence rate and distribution of giant planets at all orbital separations probed by the nearly two decades of available RV data for a statistically significant sample of solar-type stars. Our previous efforts (Wittenmyer et al. 2011a, 2016) considered simply the true 'Jupiter analogues': giant planets with $a > 3$ au moving on low-eccentricity orbits like our own Jupiter. In doing so, we hope to provide data that not only address the question of how common or unusual are planetary systems like our own, but also help to enhance our understanding of the formation and evolution of giant planets in a broader context.

In Section 2, we detail the observational data available to use, and describe the methods used to determine the occurrence rates of 'cool Jupiters' from those data. In Section 3, we present and discuss our results, before drawing our conclusions in Section 4.

2 OBSERVATIONAL DATA AND SIMULATION METHODS

We consider here a subsample of the AAPS target list that satisfies the following two criteria: an observational baseline longer than 8 yr, and more than 30 observations. This is the same selection that was used for our previous work on the occurrence rate of Jupiter analogues (Wittenmyer et al. 2011a, 2016), and it yields a sample of 203 stars.

2.1 Giant planets in the sample

This sample is known to contain 38 giant planets orbiting 30 stars, with 33 of these considered as 'cool Jupiters', as per our definition above. Given that the orbital parameters of most of these planets have not been updated since their discovery, up to a decade ago, we wish to first refine the parameters using the full extent of the latest available data. Table 1 gives the details of the various RV data sets used in our fitting. For HD 114613, HD 134987, and HD 159868, we used the corrected Keck/HIRES RVs (Butler et al. 2017) given in Tal-Or et al. (2019). Publicly available HARPS DRS velocities were obtained from the European Southern Observatory (ESO) Archive, accessed on 2019 February 1. For all data sets, where there were multiple observations in a single night, we binned them together using the weighted mean value of the velocities in each night. We adopted the quadrature sum of the rms about the mean and the mean internal uncertainty as the error bar of each binned point. We then used the SYSTEMIC *Console 2.2000* (Meschiari et al. 2009) to obtain new Keplerian orbit fits for the 33 cool Jupiters in our sample, with uncertainties derived from 10 000 bootstrap iterations. The refined orbital parameters are given in Table 2. For the HD 30177, HD 39091, and HD 73526 systems, we cite the most recent published solutions as no new data are available at present.

[1] As of 2019 October 15, just 47 of the 4073 known exoplanets were discovered through direct imaging, based on data from the NASA Exoplanet Archive.

Table 1. Properties of RV data used for refining orbits.

Star	Instrument	$N_{\rm epochs}$	Reference
HD 142	AAT	93	This work
–	ESO/HARPS	12	ESO Archive
HD 2039	AAT	46	This work
HD 13445	AAT	74	This work
HD 17051	AAT	38	This work
–	ESO/HARPS	33	ESO Archive
HD 20782	AAT	57	This work
–	PARAS	5	Kane et al. (2016)
–	ESO/HARPS	50	ESO Archive
HD 23079	AAT	40	This work
–	ESO/HARPS	26	ESO Archive
HD 23127	AAT	44	This work
–	ESO/HARPS	24	ESO Archive
HD 27442	AAT	104	This work
HD 30177	AAT	43	This work
–	ESO/HARPS	41	ESO Archive
HD 38283	AAT	67	This work
–	ESO/HARPS	5	ESO Archive
HD 39091	AAT	77	This work
–	ESO/HARPS	–	Huang et al. (2018)
HD 70642	AAT	51	This work
–	ESO/HARPS	29	ESO Archive
HD 73526	AAT	36	This work
HD 75289	AAT	50	This work
–	CORALIE	58	Udry et al. (2000)
HD 83443	AAT	25	This work
–	CORALIE	215	Mayor et al. (2004)
–	Keck/HIRES	35	Butler et al. (2017)
HD 108147	AAT	58	This work
–	CORALIE	117	Pepe et al. (2002)
HD 114613	AAT	244	This work
–	Keck/HIRES	37	Butler et al. (2017)
–	ESO/HARPS	27	ESO Archive
HD 134987	AAT	77	This work
–	Keck/HIRES	94	Butler et al. (2017)
–	ESO/HARPS	14	ESO Archive
HD 154857	AAT	45	This work
HD 159868	AAT	52	This work
–	Keck/HIRES	34	Butler et al. (2017)
HD 160691	AAT	180	This work
–	ESO/HARPS	161	ESO Archive
HD 179949	AAT	66	This work
–	McD 2.7m	17	Wittenmyer et al. (2007b)
–	Keck/HIRES	31	Butler et al. (2017)
HD 187085	AAT	75	This work
HD 196050	AAT	57	This work
–	ESO/HARPS	38	ESO Archive
HD 208487	AAT	49	This work
–	ESO/HARPS	25	ESO Archive
HD 213240	AAT	37	This work
HD 216435	AAT	79	This work
–	ESO/HARPS	13	ESO Archive
HD 216437	AAT	58	This work
–	ESO/HARPS	30	ESO Archive
HD 219077	AAT	72	This work
–	ESO/HARPS	22	ESO Archive
GJ 832	AAT	39	Wittenmyer et al. (2014c)
–	ESO/HARPS	54	Wittenmyer et al. (2014c)
–	Magellan/PFS	16	Wittenmyer et al. (2014c)

2.2 Simulation approach

To determine the underlying occurrence rates of giant planets in our sample, we must determine the degree to which incompleteness afflicts our survey data. As in numerous of our previous works (e.g. Wittenmyer et al. 2010, 2011b; Wittenmyer & Marshall 2015), we compute the detectabilities of planets by a simple injection-recovery technique. In brief, we add the Keplerian signal of an artificial planet on a circular orbit to the existing RV data, and then we attempt to recover that signal using a generalized Lomb–Scargle periodogram (Zechmeister & Kürster 2009). A planet is considered detected if it is recovered with FAP less than 1 per cent based on the FAP estimation in Zechmeister & Kürster (2009). We considered planets with 100 trial orbital periods between 100 and 6000 d, bounding the region of 'cool Jupiters' out to the time baseline of our AAPS data. The mass of the simulated planet is increased until 99 per cent of the configurations (30 values of the orbital phase) at a given period are recovered successfully. We repeated this process for recovery rates of 90, 70, 50, 30, and 10 per cent. The result is an estimate of detectability (i.e. recovery rate) for a planet of a given mass and period.

The occurrence rate of giant planets in our sample is then computed using the methods detailed in Wittenmyer et al. (2011a) and Wittenmyer et al. (2016). In brief, for each detected planet, we estimate the probability of having detected that planet using the results of the injection/recovery simulations described above, summed over the entire sample. This is accomplished by computing two quantities for each detected planet. First, for the specific P and mass of the detected planet in question, we calculate the completeness fraction $f_{\rm c}(P, M)$ for the *non-hosts* in the sample:

$$f_{\rm c}(P,M) = \frac{1}{N_{\rm stars}} \sum_{i=1}^{N} f_{\rm R,i}(P,M), \qquad (1)$$

where $f_{\rm R}(P, M)$ is the recovery rate as a function of mass at period P, and N is the total number of stars not hosting a giant planet. In this way, we account for the detectabilities for each star individually, at each of the 100 trial periods. This yields a number between 0 and 1, representing the probability that a planet with a given P and M would have been detected in the overall sample. Secondly, we calculate the recovery rate $f_{\rm R}(P_{\rm i}, M_{\rm i})$ for each detected planet, at the P and mass of that planet. This is a number between 0 and 1, representing the probability of having detected that planet given the data for that star. Usually (but not always) this number is unity; the values of $f_{\rm R} < 1$ can be thought of as cases where we 'got lucky' in detecting the planet. These two quantities are then combined in equation (2) to derive the number of expected detections given the data, and thence the number of 'missed' planets:

$$N_{\rm missed} = \sum_{i=1}^{N_{\rm hosts}} \frac{1}{f_{\rm R,i}(P_{\rm i}, M_{\rm i}) f_{\rm c}(P_{\rm i}, M_{\rm i})} - N_{\rm hosts}, \qquad (2)$$

where the symbols have the same meaning as given above. The occurrence rate of planets in a sample is then first estimated as simply the number of detections divided by the total number of stars, using binomial statistics. The completeness correction in equation (2) is then used to boost the occurrence rates and their uncertainties by a factor of $(N_{\rm missed} + N_{\rm detected})/N_{\rm detected}$ to reflect the incomplete detection efficiency of our observational data.

3 RESULTS AND DISCUSSION

We used the results of the injection-recovery simulations described above to address the two main questions posed in this paper: (1) what is the occurrence rate of giant planets as a function of orbital period, and (2) what is the frequency of *pairs* of cool giants? The first question seeks to probe the migration histories of these systems by searching for patterns in the orbital period distribution of cool giants in their final locations. With the second experiment, we seek a preliminary understanding of how common scaled-down

Table 2. Updated orbital solutions for cool Jupiters from the AAPS sample.

Planet	Period days	Eccentricity	ω degrees	T_0 BJD-2400000	K m s^{-1}	$m \sin i$ M_{Jup}	a au
HD 142b	352.48 ± 0.77	0.294 ± 0.076	303 ± 25	49876 ± 122	33.2 ± 2.8	1.268 ± 0.107	1.0467 ± 0.0015
HD 142c	6268 ± 32	0.138 ± 0.055	277 ± 27	44649 ± 2249	51.8 ± 2.5	5.35 ± 0.27	7.139 ± 0.025
HD 2039b	1110.1 ± 3.9	0.637 ± 0.011	341.7 ± 4.4	49918 ± 412	106 ± 48	4.5 ± 1.7	2.184 ± 0.006
HD 13445b	15.764 80 ± 0.000 04	0.048 ± 0.002	269.7 ± 3.3	49997 ± 6	619.2 ± 1.7	6.588 ± 0.018	0.114 340 ± 0.000 001
HD 17051b	308.3 ± 1.6	0.177 ± 0.080	62 ± 30	49873 ± 112	69.4 ± 4.6	2.49 ± 0.18	0.935 ± 0.003
HD 20782b	597.12 ± 0.07	0.952 ± 0.004	144.1 ± 1.4	49683 ± 211	117.0 ± 6.3	1.457 ± 0.049	1.374 00 ± 0.000 14
HD 23079b	724.5 ± 2.2	0.087 ± 0.031	19 ± 25	49893 ± 270	54.2 ± 1.3	2.41 ± 0.06	1.586 ± 0.003
HD 23127b	1219.5 ± 10.3	0.318 ± 0.067	187 ± 14	49970 ± 454	28.5 ± 1.7	1.54 ± 0.10	2.326 ± 0.013
HD 27442b	429.1 ± 0.7	0.057 ± 0.037	231 ± 45	49705 ± 157	32.1 ± 1.5	1.55 ± 0.07	1.269 ± 0.001
HD 30177b[1]	2524.4 ± 9.8	0.184 ± 0.012	31 ± 3	51434 ± 29	126.3 ± 1.5	8.08 ± 0.10	3.58 ± 0.01
HD 30177c	11 613 ± 1837	0.22 ± 0.14	19 ± 30	48973 ± 1211	70.8 ± 29.5	7.6 ± 3.1	9.89 ± 1.04
HD 38283b	361.0 ± 1.1	0.474 ± 0.136	188 ± 23	49842 ± 132	8.9 ± 1.6	0.289 ± 0.034	1.020 ± 0.002
HD 39091b[2]	2093.07 ± 1.73	0.637 ± 0.002	330.6 ± 0.3	45852.0 ± 3.0	192.6 ± 1.4	10.02 ± 0.15	3.10 ± 0.02
HD 70642b	2148.7 ± 9.8	0.186 ± 0.051	276 ± 14	49750 ± 784	28.0 ± 1.5	1.75 ± 0.09	3.263 ± 0.010
HD 73526b[3]	189.65 ± 0.21	0.265 ± 0.021	198.3 ± 3.6	51156.8 ± 2.6	85.4 ± 2.3	2.35 ± 0.12	0.65 ± 0.01
HD 73526c	376.93 ± 0.69	0.198 ± 0.029	294.5 ± 11.3	51051.5 ± 9.4	62.3 ± 1.8	2.19 ± 0.12	1.03 ± 0.02
HD 75289b	3.509 16 ± 0.000 02	0.062 ± 0.022	154 ± 21	49998.7 ± 1.0	54.5 ± 1.1	0.456 ± 0.010	0.0478 59 ± 0.000 002
HD 83443b	2.985 66 ± 0.000 05	0.03 ± 0.02	236 ± 43	49997.5 ± 1.1	53.8 ± 1.3	0.379 ± 0.009	0.040 464 ± 0.000 001
HD 108147b	10.9001 ± 0.0004	0.52 ± 0.05	306 ± 9	49992.8 ± 4.0	29.6 ± 2.4	0.31 ± 0.02	0.101 429 ± 0.000 002
HD 114613b	3969 ± 204	0.42 ± 0.09	208 ± 16	48351 ± 1476	4.67 ± 0.39	0.384 ± 0.047	5.29 ± 0.18
HD 134987b	258.21 ± 0.03	0.231 ± 0.006	356.0 ± 2.1	49864 ± 81	49.2 ± 0.4	1.556 ± 0.012	0.808 03 ± 0.000 07
HD 134987c	5358 ± 31	0.092 ± 0.045	295 ± 27	47167 ± 1761	8.95 ± 0.41	0.795 ± 0.036	6.100 ± 0.023
HD 154857b	408.59 ± 0.45	0.467 ± 0.018	57.4 ± 3.0	49958 ± 152	48.5 ± 1.2	2.25 ± 0.06	1.2912 ± 0.0009
HD 154857c	3515 ± 126	0.074 ± 0.054	353 ± 32	49103 ± 1309	23.6 ± 1.1	2.53 ± 0.14	5.42 ± 0.13
HD 159868b	1182.5 ± 7.0	0.006 ± 0.024	185 ± 122	49916 ± 443	38.4 ± 1.3	2.12 ± 0.07	2.252 ± 0.009
HD 159868c	351.9 ± 1.2	0.121 ± 0.045	299 ± 37	49916 ± 443	20.8 ± 1.2	0.758 ± 0.045	1.003 ± 0.002
HD 160691e	308.94 ± 0.48	0.102 ± 0.020	207 ± 68	49855 ± 53	13.4 ± 0.7	0.487 ± 0.025	0.936 ± 0.001
HD 160691b	644.68 ± 0.50	0.052 ± 0.018	25 ± 62	49518 ± 27	36.2 ± 0.3	1.684 ± 0.013	1.530 ± 0.001
HD 160691c	4043 ± 40	0.045 ± 0.015	5 ± 64	47361 ± 484	23.9 ± 0.5	2.050 ± 0.037	5.202 ± 0.030
HD 179949b	3.092 54 ± 0.000 017	0.042 ± 0.014	204 ± 25	49999 ± 1	113.4 ± 1.9	0.908 ± 0.015	0.043 923 ± 0.000 001
HD 187085b	1039.4 ± 12.1	0.157 ± 0.083	100 ± 34	48987 ± 389	14.4 ± 1.2	0.776 ± 0.068	2.100 ± 0.016
HD 196050b	1400.1 ± 8.0	0.162 ± 0.009	166 ± 10	49038 ± 522	50.2 ± 0.6	2.924 ± 0.039	2.537 ± 0.010
HD 208487b	129.3 ± 0.1	0.30 ± 0.07	88 ± 15	49970 ± 48	17.3 ± 1.5	0.442 ± 0.037	0.5186 ± 0.0003
HD 213240b	872.4 ± 2.1	0.424 ± 0.011	206.9 ± 2.1	49842 ± 321	95.8 ± 1.4	4.468 ± 0.071	1.871 ± 0.003
HD 216435b	1328 ± 20	0.481 ± 0.076	25 ± 57	49815 ± 494	21.3 ± 1.4	1.329 ± 0.085	2.541 ± 0.025
HD 216437b	1353 ± 5	0.32 ± 0.03	63 ± 6	48654 ± 490	41.1 ± 1.2	2.28 ± 0.07	2.486 ± 0.006
HD 219077b	5471 ± 52	0.769 ± 0.002	56.0 ± 0.5	46602 ± 2001	181.5 ± 0.9	10.549 ± 0.076	6.22 ± 0.04
GJ 832b[4]	3657 ± 104	0.08 ± 0.06	246 ± 22	46881 ± 250	15.4 ± 0.7	0.68 ± 0.09	3.56 ± 0.28

Note. (1) Wittenmyer et al. (2017a); (2) Huang et al. (2018); (3) Wittenmyer et al. (2014a); (4) Wittenmyer et al. (2014c).

Solar system analogues might be (i.e. systems with two cool giants analogous to Jupiter and Saturn).

3.1 Period distribution of Jupiters hot and cool

To investigate the occurrence rate of giant planets as a function of orbital period, we divided the period range into evenly sized bins in log space ($\Delta \log P = 0.5$). We then computed the missed-planet corrections (equation 2) and occurrence rates in each bin based on the detections from our sample. Table 3 summarizes the results, and Fig. 1 shows the occurrence rates in their orbital period bins.

In previous studies, the existence of a 'period valley' in the distribution of exoplanet orbits has become well established (e.g. Jones et al. 2003; Udry et al. 2003; Wittenmyer et al. 2010). That 'valley' is a range of orbital periods in which few planets are detected – ranging between ∼30 and ∼100 d. The 'period valley' can be clearly seen in our data, in the form of an empty bin for periods between 30 and 100 d.

For periods $P < 400$ d, our results are consistent with the ∼4 per cent occurrence rate found by Santerne et al. (2016). The occurrence rate of giant planets plateaus at longer periods, but it does not appear to fall off, in contrast to the findings of Fernandes et al. (2019), who found evidence for a turnover in the occurrence rates at periods of 1000–2000 d. However, our sample size is considerably smaller, such that, within our uncertainties (Fig. 1), we cannot exclude the fall off at the snow line postulated by Fernandes et al. (2019). For the 'Jupiter analogues' at periods $P > 3000$ d, our results remain consistent with the literature (e.g. Cumming et al. 2008; Zechmeister et al. 2013; Rowan et al. 2016; Wittenmyer et al. 2016).

Cumming et al. (2008) and Petigura et al. (2018) found an increase in occurrence by a factor of ∼5 in the 100–300 d bin compared to shorter periods, but we find that bin enhanced by at most a factor of 2, with large uncertainties. This is almost certainly due to the small number of planets in our sample [Petigura et al. (2018) used the entire California Planet Search and *Kepler* samples]. We note that the AAPS sample of long-period giant planets has the potential to be expanded with further observations (Wittenmyer et al. 2017b) from other precise RV facilities such as MINERVA-Australis (Addison et al. 2019). Consistent with Petigura et al. (2018) and Cumming et al. (2008), we do find a generally increasing giant-planet occurrence rate with orbital period.

Table 3. Completeness corrections for the known giant planets in our data set, as a function of their orbital period.

Planet	f_R	f_c
Period bin: 1–3 d – $0.5^{+1.4}_{-0.2}$ per cent	–	–
HD 83443b	1.00	1.0000
Period bin: 3–10 d – $1.0^{+1.6}_{-0.5}$ per cent	–	–
HD 179949b	1.00	1.0000
HD 75289b	1.00	1.0000
Period bin: 10–30 d – $1.0^{+1.6}_{-0.5}$ per cent	–	–
HD 108147b	1.00	1.0000
HD 13445b	1.00	1.0000
Period bin: 30–100 d – $0.0^{+1.2}_{-0.0}$ per cent	–	–
Period bin: 100–300 d – $1.7^{+1.9}_{-0.7}$ per cent	–	–
HD 208487b	0.95	0.8052
HD 73526b	1.00	0.9980
HD 134987b	1.00	0.9780
Period bin: 300–1000 d – $8.0^{+3.7}_{-2.2}$ per cent	–	–
HD 17051b	0.96	0.9953
HD 160691e	1.00	0.7250
HD 159868c	1.00	0.8737
HD 142b	1.00	0.9641
HD 38283b	0.50	0.4448
HD 73526c	1.00	0.9917
HD 154857b	1.00	0.9875
HD 27442b	1.00	0.9656
HD 20782b	0.95	0.9568
HD 160691b	1.00	0.9651
HD 23079b	1.00	0.9859
HD 213240b	1.00	0.9984
Period bin: 1000–3000 d – $5.3^{+2.8}_{-1.5}$ per cent	–	–
HD 187085b	1.00	0.7565
HD 2039b	1.00	0.9964
HD 159868b	1.00	0.9674
HD 23127	0.94	0.9254
HD 216435b	1.00	0.9005
HD 216437b	1.00	0.9622
HD 196050b	1.00	0.9845
HD 39091b	1.00	1.0000
HD 70642b	1.00	0.9306
HD 30177b	1.00	1.0000
Period bin: 3000–10 000 d – $6.9^{+4.2}_{-2.1}$ per cent	–	–
HD 154857c	1.00	0.9467
GJ 832b	1.00	0.4672
HD 114613b	1.00	0.2092
HD 160691c	1.00	0.8990
HD 134987c	1.00	0.5072
HD 219077b	1.00	0.9995
HD 142c	1.00	0.9944
HD 30177c	1.00	0.9990

3.2 Do cool Jupiters come in pairs?

Of the 203 AAPS stars considered here, 25 (12.3 per cent) have at least 1 cool Jupiter, and 7 (3.4 per cent) have multiple such planets. That is, if a star hosts one cool giant, it has an ∼25 per cent probability of hosting additional cool giants that could be detected using current methods. We used the injection-recovery simulations as above to correct for incompleteness. One subtle difference here is that, now that we are considering multiple-planet systems, the identity of the 'detected' planet in equation 2 becomes ambiguous. We repeated the calculations considering both the first and second giant planets discovered. One can imagine that, in considering the second detected planet, the recovery rate $f_R(P_i, M_i)$ for its period and mass would be lower than that for the first detected planet (i.e. the second planet is less obvious and hence harder to detect). Indeed, we find this to be the case: When considering the second detected planet, we arrive at 1.27 missed planets among the 7 multiples, while we only estimate 0.15 missed planets when considering the first planet discovered in the multiple systems. When applying these correction factors to the binomial statistics as in the previous subsection, we arrive at statistically identical occurrence rates of cool-giant pairs regardless of which is detected first: $4.0^{+2.7}_{-1.3}$ per cent (second planet) and $3.5^{+2.3}_{-1.1}$ per cent (first planet).

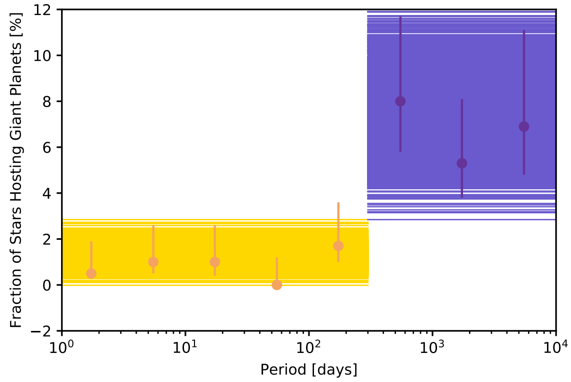

Figure 1. Frequency of giant planets as a function of orbital period.

Gould et al. (2010) presented the first analysis of the occurrence rate of multiple giant planets beyond the snow line. Based on microlensing results, including one detection of a Jupiter/Saturn analogue pair (Gaudi et al. 2008), they estimated that about 1/6 (17 per cent) of stars host multiple cold giants akin to our Solar system. Although that estimate is somewhat higher than that which we obtain in this work, it is worth remembering that detections using microlensing are sensitive to planets at very large orbital radii, while the data set presented herein is only sensitive to planets with orbital periods $P \lesssim 6000$ d (a ∼7–8 au). As such, it seems reasonable to assume that as we become ever more sensitive to planets of lower mass and planets at larger orbital radii, the planetary abundances we determine will continue to climb.

In the regime of small samples and/or high incompleteness, the derived occurrence rates can be sensitive to the injection/recovery techniques. Improved techniques and higher quality data can result in increased planet occurrence rates (which, strictly speaking, ought not to happen if the incompleteness corrections are performed perfectly). For example, the early *Kepler* planet occurrence rate papers showed a turnover in the frequency of small planets, with a peak near ∼2.5 $R_\oplus$ and a drop for smaller planets (e.g. Howard et al. 2012; Fressin et al. 2013; Petigura et al. 2013). Subsequent analysis on the *Kepler* Q1–Q16 data by Burke et al. (2015) showed instead a monotonically rising occurrence rate down to ∼1 $R_\oplus$ (cf. their fig. 8). The latter work directly injected the simulated planets into the raw photometry and processed the data through the usual pipelines, to produce a more robust result. Similarly, it is possible that the derived occurrence rates for long-period giant planets may increase in future as new data reduce the impact of incompleteness. For long-period, low-amplitude planets, astrophysical and instrumental factors may also affect detectability. Stellar magnetic activity cycles are a significant concern when considering RV signals of periods

10–20 yr and amplitudes of only a few m s^{-1} (Johnson et al. 2016; Yee et al. 2018), since such signals can easily be produced both by activity cycles and by Saturn analogues (the RV signal of Saturn is 3 m s^{-1} over 30 yr). Long-term RV surveys must also be careful in accounting for small (∼1 m s^{-1}) offsets caused by instrumental factors such as hardware upgrades or aging calibration lamps (Lo Curto et al. 2015; Tal-Or et al. 2019).

In the coming years, as surveys such as MINERVA-Australis (Addison et al. 2019) take the mantle of continuing the work of the old RV surveys (such as AAPS), we expect to be able to extend our study to longer orbital periods. The improved sensitivity of those new instruments (which aim to achieve precisions of ∼1 m s^{-1} for quiet stars), combined with the wealth of astrometric data that should become available from the *Gaia* spacecraft, it seems likely that we will be able to extend our work to consider the abundance of less massive planets, as well as those on still longer period orbits, working towards the detection of true analogues for the Solar system's ice giants, Uranus and Neptune.

4 CONCLUSIONS

A key legacy of the 18-yr AAPS is the high efficiency with which that survey detected giant planets moving on long-period orbits. While other more recent RV surveys have achieved better measurement precision, and hence have discovered and characterized a great many low-mass super-Earths and sub-Neptunes (e.g. Borsato et al. 2019; Feng et al. 2019; Udry et al. 2019), the venerable AAPS has greatly contributed to our understanding of cool Jupiters. There is ultimately no substitute for time.

In this work, we have examined the occurrence rates of such planets across a wide swathe of orbital period space. Our main conclusions are as follows:

(i) We find that giant planets are about eight times more commonly found in orbits beyond about 1 au than in closer-in orbits.

(ii) There are no significant differences in the occurrence rate of gas giants beyond ∼1 au.

Although it is still unclear why gas giants with orbital distance within ∼1 au exist at all, the preservation of this sharp transition implies that planet–planet scattering (due to dynamical instabilities) has not greatly altered the kinematic structure of planetary architecture.

The transition semimajor axis may correspond to the snow line, which implies the inner boundary of the birth domain. That we see a transition near 1 au is somewhat unexpected based on the classic definition of snow line (Hayashi 1981), which is about 2.7 au away from the Sun. Sasselov & Lecar (2000), however, found that snowlines could be as close as 1 au to the central stars. Even so, whether the closer region is a forbidden zone for gas giant formation is still under severe debate (Batygin et al. 2016). Our result implies that gas giants are less likely to be formed in the inner region of a system, but it is still possible. However, the big conflict between the *in situ* formation model and current observational results is that hot Jupiters appear to be as common as warm Jupiters. Hot super-Earths, however, are much less common than cold super-Earths (See Dawson & Johnson 2018).

The transition semimajor axis may also be the location where photoevaporation of the disc gas occurs. It may lead to divergence in the migration outcome (i.e. planets inside it migrate inwards and planets outside it migrate outwards). But the process corresponding to that time-scale of migration is similar to (or slightly longer than) the time-scale of disc depletion. There are some uncertainties, however, on these two migration time-scales (Ida & Lin 2004).

In the future, as the true distribution and occurrence of planets at larger orbital radii becomes clearer, data such as ours will doubtless prove vital in constraining different models of exoplanet formation. Rather than simply explaining a given population of exoplanets (such as the hot Jupiters), such results will allow theorists to build models of planet formation that cover a wide variety of initial conditions – from stellar mass and disc mass to the metallicity of the system as it forms.

Finally, we note that while the focus of interest in exoplanetary science has been on the revolution wrought by the space-based transit missions of *Kepler* and *TESS* (Borucki et al. 2010; Ricker et al. 2015), and that further exciting insights will undoubtedly be gained from future missions, there remains a need to continue the legacy RV work highlighted here. For it is only with such continued, daresay a multigenerational effort, that we will come to understand the *complete* architectures of planetary systems, probing out to Saturn analogues and beyond. And at the end of all our exploring, we will come to a better understanding of our own Solar system in the Galactic context.

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APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material that would interrupt the flow of the main paper, it can be placed in an appendix that appears after the list of references.

This paper has been typeset from a TEX/LATEX file prepared by the author.