Continued Kinematic and Photometric Investigations of Hierarchical Solar-type Multiple Star Systems

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Abstract
We observed 15 of the solar-type binaries within 67 pc of the Sun previously observed by the Robo-AO system in the visible, with the PHARO near-infrared camera and the PALM-3000 adaptive optics system on the 5 m Hale telescope. The physical status of the binaries is confirmed through common proper motion and detection of orbital motion. In the process, we detected a new candidate companion to HIP 95309. We also resolved the primary of HIP 110626 into a close binary, making that system a triple. These detections increase the completeness of the multiplicity survey of the solar-type stars within 67 pc of the Sun. Combining our observations of HIP 103455 with archival astrometric measurements and RV measurements, we are able to compute the first orbit of HIP 103455, showing that the binary has a 68 year period. We place the components on a color–magnitude diagram and discuss each multiple system individually.

Key words: binaries: visual – instrumentation: adaptive optics – stars: solar-type

1. Introduction
We report observations of stellar multiple systems with adaptive optics (AO), completing the program of Roberts et al. (2015, hereafter Paper I). The program’s goal is the characterization of hierarchical multiplicity of solar-type stars in the solar neighborhood. This is a follow-up to the large multiplicity survey conducted with the Robo-AO system (Riddle et al. 2015, R15). As in Paper I, we observed multiple systems discovered in R15 to confirm the bound nature of their companions by relative astrometry and infrared (IR) photometry. New subsystems discovered serendipitously in Paper I were re-visited here to follow their orbital motion, with the eventual goal of determining orbits and masses. In fact, we are already able to compute one orbit by combining new and archival data of HIP 103455.

The motivation for this program was presented in Paper I. Continued interest in the multiplicity of solar-type stars, already well characterized, is driven by the need to clarify the properties of hierarchical systems with three or more stars. Hierarchies open new insights on formation mechanisms of binaries by their relative frequency, statistics of period ratios, eccentricities, and relative orbit orientations. Compared to binaries, hierarchies are more difficult to study, requiring combinations of observing techniques, so much work remains before we attain a good knowledge of hierarchical systems even in the close solar neighborhood. In addition, the period ratio between the closer and wider pairs of hierarchical multiples differs by at least half an order of magnitude, contributing to the complications for multiplicity studies. Our observations provide an incremental input to this effort.

Additional interest in the multiplicity of solar neighbors stems from the fact that many of these stars host exoplanets (Raghavan et al. 2006; Bonavita & Desidera 2007). The emerging statistics show that exoplanets are ubiquitous, so many stars not currently known as exoplanet hosts will join this family in the future. Planet formation and evolution are closely related to the multiplicity of the host stars, hence the need to explore the multiplicity of these stars as best as we can.

New observations are described in Section 2, and their results are given in Section 3. Comments on individual systems are given in Section 4, while Section 5 presents the combined visual–spectroscopic orbit of HIP 103455. The results are summarized in Section 6.

2. Observations
We observed the stars on 2015 July 7 UT with the Palomar Observatory Hale 5 m telescope using the PALM-3000 natural guide-star AO system (Dekany et al. 2013) and the PHARO near-IR camera (Hayward et al. 2001). We collected 50 frames of each object with an exposure time of 1.416 s, which is the minimum exposure for PHARO. The data were reduced by debiasing, flat fielding, bad pixel correction, and background subtraction and then shift-and-added to create a single image. The fitstars algorithm was used to measure the astrometry and photometry of the objects (ten Brummelaar et al. 1996, 2000).

We observed three calibration binaries4 on the same night as the science targets; see Table 1. We compared their measured astrometry with the ephemeris predicted from their orbits and used the results to compute the plate scale and the position angle offset, \(24.9 \pm 0.2\) mas pixel\(^{-1}\) and \(0^\circ 77 \pm 0^\circ 5\). Since astrometric calibration based on orbits includes the errors in the orbits, we have presented the measured differential pixel locations and the orbits used to calibrate the binaries in Table 1. This allows the reader to judge the calibration accuracy and future readers to recompute the astrometric calibration if improved orbits become available. Error bars on the astrometry were computed using the technique in Roberts et al. (2015). Photometric error bars were assigned using the technique described in Roberts et al. (2005).

4 http://ad.usno.navy.mil/wds/orb6/orb6c.html
3. Astrometry, Photometry, and Color–Magnitude Diagrams (CMDs)

New information resulting from our observations is highlighted in this Section. Table 2 contains information on 15 solar-type systems: four binaries, nine triples, one quadruple, and one quintuple. We are able to confirm the physical nature of four Robo-AO candidate companions: HIP 94666, HIP 94905, HIP 95309, and HIP 110626. The table gives the Washington Double Star (WDS) Catalog designation for the system as well as the HD and HIP numbers for the primary star. This is followed by the discoverer designation, the known multiplicity of the system, the observation epoch, the astrometry, and the differential photometry of the pair listed in the discovery designation. For systems where we detected more than two components in the system, we have only listed the multiplicity for the first pair. New discoveries are marked with a footnote to the WDS designation. For some of the closer systems we used an alternative blind-deconvolution code and these are also marked with a footnote.

For the observed systems, we have estimated their orbital periods. There are a few ways to estimate the periods of binaries with only a handful of astrometric measurements. One, $P^*$, is based on the projected separation when we know the distance to the system (Tokovinin 2014); in most cases it is within a factor of three from the true period. The other is based on the angular velocity and the assumption that the system has a circular face-on orbit. Both techniques provide rough order-of-magnitude estimates, but which is more accurate? To help answer this question, we simulated a population of binaries with random orientation and with the thermal and sine eccentricity distributions (Tokovinin & Kiyava 2016, average eccentricity 0.67 and 0.5, respectively). Figure 1 shows the cumulative distribution of the angular speed normalized by the
circular-orbit speed. The medians are 0.33 and 0.48 for the thermal and sine eccentricity distributions. So, the binary period estimated from angular speed, $P = \frac{360\,^\circ}{\dot{\theta}}$, where $\dot{\theta}$ is the rate of position angle change, is longer than the true period by a factor of 2 to 3 in half of the cases and longer than the true period in 90% of the cases. Binaries spend a significant fraction of time moving slower than average and "catch up" to complete the full revolution in $P$ years during short time intervals. Both estimation techniques make only order-of-magnitude, statistical estimates, but $P^*$ is biased less than $P_c$. As such, we provide period estimates based on $P^*$.

Differential photometry in the $J$ and $K_s$ bands from Table 2 and combined magnitudes of stellar systems from 2MASS allow us to compute the individual magnitudes of resolved components and place them on the CMD using *Hipparcos* parallaxes. To extend the color base, we also use the SDSS $i'$ magnitudes, with the differential photometry from R15 and the combined magnitudes evaluated by interpolation from other bands, as explained in Paper I. The two CMDs are shown in Figure 2. In calculating the error bars, we assigned errors of 0.1 mag to the differential photometry from R15 and assumed reasonable errors for the combined magnitudes. At an average distance of 50 pc, the 1 mas parallax error (the largest of any of

Figure 2. Color–magnitude diagrams. Left: in the $i'$, $i' - K_s$ bands, right: in the $J$, $J - K_s$ bands. Asterisks denote primary components, squares with error bars are secondary components. Full and dashed lines are Dartmouth 1 Gyr isochrones (Dotter et al. 2008) for solar metallicity and [Fe/H] = −0.5, respectively.

| HIP   | $\varpi_{\text{ Hip}}$ (mas) | Comp | $i'_{\text{abs}}$ (mag) | $J_{\text{abs}}$ (mag) | $i' - K_s$ (mag) | $J - K_s$ (mag) |
|-------|-------------------------------|------|--------------------------|------------------------|------------------|------------------|
| 69160 | 17.6 ± 0.9                    | A    | 4.33                     | 3.66                   | 1.06 ± 0.07      | 0.39 ± 0.07      |
|       |                               | B    | 5.05                     | 3.91                   | 1.51 ± 0.09      | 0.37 ± 0.09      |
| 75676 | 31.1 ± 0.6                    | B    | 6.53                     | 5.23                   | 1.95 ± 0.04      | 0.65 ± 0.05      |
|       |                               | C    | 8.01                     | 6.33                   | 2.44 ± 0.09      | 0.76 ± 0.09      |
| 85042 | 51.2 ± 0.4                    | B    | 9.70                     | 7.55                   | 2.98 ± 0.06      | 0.83 ± 0.04      |
|       |                               | C    | 9.70                     | 7.56                   | 2.94 ± 0.06      | 0.80 ± 0.04      |
| 86642 | 24.7 ± 0.5                    | A    | 3.94                     | 3.94                   | 1.23 ± 0.04      | 1.23 ± 0.04      |
|       |                               | B    | 8.94                     | 8.94                   | 2.63 ± 0.20      | 2.63 ± 0.20      |
| 91120 | 20.2 ± 0.4                    | Ba   | 6.99                     | 5.42                   | 2.33 ± 0.06      | 0.76 ± 0.05      |
|       |                               | Bb   | 7.82                     | 6.38                   | 2.05 ± 0.11      | 0.61 ± 0.11      |
| 94666 | 15.5 ± 0.6                    | A    | 3.41                     | 2.56                   | 1.16 ± 0.04      | 0.31 ± 0.04      |
|       |                               | B    | 9.12                     | 7.61                   | 2.42 ± 0.50      | 0.91 ± 0.18      |
| 94905 | 26.7 ± 0.6                    | A    | 3.92                     | 3.12                   | 1.08 ± 0.04      | 0.29 ± 0.04      |
|       |                               | B    | 8.77                     | 7.30                   | 2.48 ± 0.20      | 1.02 ± 0.08      |
| 95309 | 21.7 ± 1.0                    | A    | 4.29                     | 3.44                   | 1.23 ± 0.04      | 0.38 ± 0.04      |
|       |                               | B    | 9.02                     | 7.39                   | 2.53 ± 0.20      | 0.90 ± 0.08      |
|       |                               | C    | ...                      | 7.24                   | ...              | 1.85 ± 0.08      |
| 101234| 15.1 ± 0.9                    | A    | ...                      | 2.81                   | ...              | 0.29 ± 0.08      |
|       |                               | B    | ...                      | 4.86                   | ...              | 0.44 ± 0.40      |
| 103455| 31.6 ± 0.6                    | A    | 4.15                     | 3.33                   | 1.10 ± 0.04      | 0.28 ± 0.04      |
|       |                               | B    | 8.82                     | 6.56                   | 3.03 ± 0.21      | 0.77 ± 0.26      |
| 109361| 23.3 ± 0.6                    | A    | ...                      | 3.31                   | ...              | 0.27 ± 0.04      |
|       |                               | B    | ...                      | 5.52                   | ...              | 0.72 ± 0.17      |
| 110626| 20.3 ± 0.9                    | A    | 4.25                     | 3.31                   | 1.19 ± 0.04      | 0.31 ± 0.04      |
|       |                               | B    | 10.27                    | 5.52                   | 3.08 ± 0.30      | 1.02 ± 0.17      |
|       |                               | C    | ...                      | 6.80                   | ...              | 0.62 ± 0.22      |
| 118213| 20.2 ± 0.7                    | A    | 4.48                     | ...                    | 1.28 ± 0.04      | ...              |
|       |                               | B    | 11.04                    | ...                    | 3.00 ± 0.30      | ...              |
our systems) translates to a 5% distance error or 0.1 mag in absolute magnitudes, which is well within the natural CMD uncertainty caused by age and metallicity differences and imperfect isochrones. Table 3 lists absolute magnitudes and colors of individual components computed from the differential and combined photometry and used to plot the CMDs in Figure 2. Using absolute magnitudes, we estimate masses of secondary components by assuming that they are located on the main sequence.

4. Comments on Individual Systems

HIP 69160 (HD 123760 = WDS 14094+1015) is an SB2 with an 8 yr period. The SB2 designation for this pair comes from Tokovinin (2014), who also provided the input for the R15 survey observing list, which Paper I and this work are now following up. A companion was resolved by R15 and it is confirmed by our observations. The companion’s position angle has changed by 11° in the 2.5 yr since it was discovered. The semimajor axis estimated from period is 92 mas, which is close to the measured separation. It seems likely that the system is near apastron and is at its slowest part of the orbit. If so, the eccentricity of the orbit is probably high. The alternative, that this is a wider tertiary companion to an unresolved SB2, is unlikely, considering that small $\Delta m$ matches the large spectroscopic mass ratio and the separation matches the SB2 axis.

HIP 75676 (HD 138004 = WDS 15277+4253) (A), together with BC at 40°,2, form a wide physical pair. The BC binary was first observed by R15 and confirmed by our observation. Its component B is a 17 day spectroscopic pair (Tokovinin 2014), while the star A is a spectroscopic and astrometric binary (Makarov & Kaplan 2005), meaning that this is a quintuple stellar system. We provide IR photometry of the pair BC with an estimated period of 40 yr. Its position angle changed by 13°. While the magnitude of the proper motion (PM) and the orbital motion are similar, they are moving in different directions and we conclude that this system has common PM.

HIP 85042 (HD 157347 = WDS 17229-0223) is a visual triple, with a wide 46° AB pair (Raghavan et al. 2010) and the BC pair consisting of two M dwarfs (R15). Our observations confirm the earlier detection of R15. The estimated period of BC is $\sim 40$ yr. The magnitude of the PM of the primary is roughly 10 times the orbital motion, leading us to conclude that this system has a common PM.

HIP 86642 (HD 161163 = WDS 17422+3804) is a triple system. The 6 yr spectroscopic subsystem Aa, Ab (Tokovinin 2014) was resolved in Paper I, where the physical nature of the wide pair detected by R15 was also established. As this system has a short period, it should be observed as often as possible, so that a combined visual/spectroscopic orbit can be computed.

HIP 91120 (HD 171886 = WDS 18352+4135). We resolved the subsystem Ba,Bb discovered with Robo-AO at 0°14 and 336°, now closing to 0°08 and 16°. Its estimated period is 16 yr, and the observed orbital motion is indeed fast. The primary’s PM is larger than the orbital motion including the large error bar on the position angle and we conclude the system has a common PM.

HIP 94666 (HD 180683 = WDS 19158+3823). The physical nature of the 3°6 tertiary companion to this spectroscopic binary (Tokovinin 2014) is confirmed by the large PM of the primary compared to the tiny orbital motion between the observation of R15 and our current measurement. Our photometry places the secondary on the main sequence, its mass is $\sim 0.37 M_\odot$.

HIP 94905 (HD 181144 = WDS 19188+1629). The nature of the tertiary companion B, at 6°9 from the spectroscopic binary (Tokovinin 2014), was controversial considering that the system is located in the Galactic plane with dense stellar background, while its HIP2 PM is slow, 30 mas yr$^{-1}$. Comparison of our astrometry with 2MASS, as well as our resolved photometry, indicate that the pair AB is physical. Its position would have changed by 0°45 since the 2MASS epoch if B had a zero PM.

HIP 95309 (HD 182335 = WDS 19234+2034) is another object in the Galactic plane, with a moderate PM of (+13, −186) mas yr$^{-1}$. The physical nature of B is confirmed by its stable position and its location on the main sequence in the CMDs. Unexpectedly, we have discovered a new component C with a separation of 3°1, between A and B (see Figure 3(a)). The new component, C, is brighter than B, but it was not seen in the $i'$ band with Robo-AO (R15). We measure its color $J − K_s = 1.85$ mag, much redder than any normal dwarf star. The nature of C is enigmatic, as most stars around HIP 95309 in the 2MASS $K_s$-band image are fainter and it is difficult to figure out how C could project on the AB pair without being noticed before. It could be either a distant red transient, or a nearby low-mass brown dwarf with a very fast PM.

HIP 101234 (HD 195872 = WDS 20312+5653) was re-observed to confirm its substantial magnitude difference established in Paper I and discrepant with the $\Delta i'$ $\sim 0$ measured with Robo-AO. The period is about 30 yr, and the pair turned by 44° since 2012.76. The observed motion matches the estimated period, but more data are needed before attempting to compute the orbit. The differential magnitudes measured in 2015 are within the error bars of the differential magnitudes measured in Paper I and do not shed any light on why they are so different from those measured in R15.

HIP 101430 (HD 195992 = WDS 20333+3323) was observed in Paper I and the B component was revealed to be a close binary with an estimated period of $\sim 30$ yr. This paper’s observations show direct motion and the binary opening up. The A component was saturated and we were unable to measure the astrometry of the A, Ba, or AE pairs.

HIP 103435 (HD 199598 = WDS 20577+2624). The new measurement combined with existing data leads to the determination of the orbit in Section 5.

HIP 109361 (HD 210388 = WDS 22094+3508) is an 18.5 yr spectroscopic binary (Tokovinin 2014) that turned by 13° since its resolution with Robo-AO.

HIP 110626 (HD 212585 = WDS 22246+3926). We resolved the inner astrometric (Makarov & Kaplan 2005) and spectroscopic subsystem Aa, Ab (Tokovinin 2014) at 0°22 separation (see Figure 3(b)). From the projected separation, the estimated orbital period is $\sim 30$ yr. Robo-AO was unable to resolve the system due to the large contrast, $\Delta K = 3.1$, between the two components. The component B has the luminosity of a $\sim 0.23 M_\odot$ dwarf.

HIP 110785 (HD 212754 = WDS 22266+0424) is a triple system with a wide pair in a 420 yr period (Hale 1994), with a primary consisting of a spectroscopic binary (Tokovinin 2014) with a 931 day period (Griffin 2010). Despite the spectroscopic binary’s semimajor axis of 59 mas, we were unable to resolve the subsystem owing to the small mass ratio of 0.22 determined.
HIP 118213 (HD 224531 = WDS 23588+3156) is a triple system similar to HIP 110626, where the inner astrometric (Makarov & Kaplan 2005) and spectroscopic pair Aa,Ab (Tokovinin 2014) was first resolved in Paper I. We confirm the large magnitude difference between Aa and Ab, $\Delta K_s = 4.4$ mag. The separation implies an orbital period of $\sim 100$ yr; the mass of Ab is estimated at $0.2 \, M_\odot$. The AB pair shows hardly any motion between the R15 observation in 2012 and 2015. The PM of the system is high enough that the system is clearly physical.
Table 4
Orbital Elements of HIP 103455

| Element          | Value          |
|------------------|----------------|
| $P$ (years)      | 68.2 ± 1.5     |
| $a$ (")         | 0.620 ± 0.025  |
| $i$ (°)         | 154.3 ± 8.5    |
| $\Omega$ (°)    | 326.7 ± 2.0    |
| $T$             | 2003.4771 ± 0.0006 |
| $e$             | 0.774 ± 0.004  |
| $\omega$ (°)    | 84.3 ± 0.2     |
| $K_1$ (kms$^{-1}$) | 1.091 ± 0.001 |
| $V_0$ (kms$^{-1}$) | −0.859 ± 0.002 |

5. Orbit of HIP 103455

The solar-type star HIP 103455 (HD 199598, G0V, $V = 6.90$) has a distance of 30 pc (van Leeuwen 2007). It is an X-ray source 1RXS J205739.4+262420, indicating relative youth (Guillout et al. 2009). It was observed with AO at Palomar in 2003 among other young stars and found unresolved (Metchev & Hillenbrand 2009). However, the Robo-AO system resolved it into a 0.6" binary in 2012 and 2013 (Riddle et al. 2015). This was confirmed in July 2015 (Paper I). The separation is increasing, showing some orbital motion, with an estimated period of ~60 yr. S. Metchev (2015, private communication) re-examined the Palomar data of 2003 and detected the companion overlapping with the first diffraction ring at a separation of 0.6".

The binarity of HIP 103455 was established independently by its variable radial velocity (RV). Using precise RV measurements, Patel et al. (2007) suggested a probable orbit with a poorly constrained period around 60 yr and a large eccentricity of approximately 0.7. The RV amplitude was small, only 1.1 km s$^{-1}$, indicating a companion of low mass, $M_2 = 0.12 M_\odot$. Direct resolution of this binary means that the companion is in fact more massive and the small RV amplitude is caused by the low orbital inclination. Interestingly, Nidever et al. (2002) did not detect any significant RV variation over one year in the initial RV data from Lick.

The third independent evidence of binarity comes from the astrometry. The PM differs from the long-term ground-based PM by 7 mas yr$^{-1}$. This is a so-called $\Delta \mu$ binary according to Makarov & Kaplan (2005). Modeling detection of such astrometric binaries shows that their typical periods are a few decades (Tokovinin et al. 2012).

We searched the data archives and located images of HIP 103455 taken with the Gemini Telescope and the Hokupa’a AO system using the QUIRC science camera (Graves et al. 1998). In the images the star was located at different positions across the detector. We fitted a plane to each image and subtracted it off. Next, we subtracted off the median of all the “de-planed” images. This resulted in 22 images. We then measured the astrometry of each image using fitstars. The error bars were set equal to the standard deviation of the measurements.

We computed a combined orbital solution using the ORBITX code (Tokovinin 1992). ORBITX uses the Levenberg–Marquardt method to solve for all the orbital elements. The resolved measurements come from the archival QUIRC data (S. Metchev 2015, private communication), Robo-AO (Riddle et al. 2015), PHARO (Roberts et al. 2015), and this paper. The individual RVs were published by Fischer et al. (2014), covering the period from 1998.5 to 2011.8. The RV measurement accuracy is about 10 m s$^{-1}$. Passage through theperiastron in this eccentric orbit has been well observed.

The orbit is shown in Figures 4 and 5, and its elements are given in Table 4. Astrometric measurements and their deviations from the orbit are assembled in Table 5. Altogether, the orbit matches the available data quite well, with weighted rms residuals of 0.5" in angle, 10 mas in separation, and 12 m s$^{-1}$ in RV. The mass sum is $1.62 M_\odot$. The RV amplitude and inclination give the companion mass $M_2$ of 0.27 $M_\odot$ assuming 1.1 $M_\odot$ for the primary. However, the large error of inclination implies a large uncertainty of $M_2$.

The period and mass ratio of HIP 103455 place it among other common solar-type binaries. The available precise RV data exclude any short-period companions to the main component A, except maybe low-mass planets. However, the large eccentricity truncated the circumstellar disk and likely prevented formation of planets. The mass of the secondary component B is constrained by its RV amplitude and its brightness. It is located above the main sequence in the $(i^2, i^2 - K_s)$ CMD and on the main sequence in the $(J, J - K_s)$ CMD in Figure 2, while A lies on the main sequence. The Galactic velocity $(U, V, W) = (-44.4, -16.4, -16.8)$ km s$^{-1}$, computed without correction for orbital motion, corresponds to the young disk kinematics but does not match any known kinematic groups. If the component B is indeed a pre-main-sequence star, its mass may be measured accurately in the future by monitoring the orbital motion. The separation is large enough that it is possible to collect individual spectra under good seeing (or with AO). These spectra can then be used to derive stellar parameters and look for signatures of young age.

6. Summary

The observations presented in Paper I resolved for the first time six new pairs, some of them totally unexpected. Here, we add the first resolution of the spectroscopic and astrometric pair HIP 110626 and the discovery of an enigmatic red companion to HIP 95309. We confirmed several pairs from Paper I and

Table 5
Astrometry and Residuals of HIP 103455

| Date (years) | $\theta$ (°) | $\rho$ (°) | $\sigma$ (°) | $(O-C)_0$ (°) | $(O-C)_\rho$ (°) | Instrument/Reference |
|-------------|-------------|------------|-------------|---------------|-----------------|---------------------|
| 2001.487    | 332.0       | 0.238      | 0.020       | 2.9           | −0.001          | QUIRC/Gemini 8 m    |
| 2003.720    | 228.0       | 0.110      | 0.010       | 2.3           | −0.019          | S. Metchev (2015, private communication) |
| 2012.766    | 102.8       | 0.610      | 0.010       | 0.1           | −0.004          | Riddle et al. (2015) |
| 2013.622    | 99.8        | 0.639      | 0.010       | −0.4          | −0.005          | Riddle et al. (2015) |
| 2013.837    | 100.1       | 0.600      | 0.010       | 0.5           | 0.009           | Roberts et al. (2015) |
| 2015.514    | 93.7        | 0.72       | 0.010       | 0.9           | 0.015           | PHARO/Hale 5 m      |
started to observe their orbital motion. The physical nature of several binaries from R15 with separations of several arcseconds is established using photometry and astrometry presented here. We derived the first orbit of the 68 year pair HIP 103455 Although it is not yet fully covered by resolved observations and RVs, the available data already constrain the orbital elements. This system is likely young, and its further study may be of interest for calibrating masses.

This work is a modest and incremental contribution to our knowledge of the multiplicity of solar-type stars. Eventually planets will be discovered around some stars observed here, and then our observations will become even more valuable, adding a “look-back” perspective to future studies of those systems. This aspect is nicely illustrated here by the role of archival data in the orbital analysis of HIP 103455.

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Facilities: Hale (PALM-3000, PHARO), Gemini (Hokupa’a, QUIRC).

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