Collaboration and Competition in ExoPlanet Research

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Abstract.
Collaboration and competition are strong driving forces in the modern search for exoplanets, appears between individuals, agencies and nations as well as between observing techniques and theoretical interpretation. I will argue that these forces, taken in balance, are beneficial to the field and are partly responsible for the rapid progress in the search for planets and ultimately the search for life beyond the solar system. Specific examples will include indirect detection of Earth analogs from ground and space and the direct detection of gas giant and terrestrial planets.

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COMPETITION, COLLABORATION AND COORDINATION

My talk will focus on the positive aspects of collaboration and competition in the field of exoplanet science. I take the terms “collaboration" and “competition" in their broadest senses, encompassing interactions between individual groups, agencies, countries, measurement techniques, and different observatory facilities on the ground or in space.

The history of the search for other planets is the story of competition and collaboration. A short recap of the discovery of Neptune illustrates this point [14]. In September, 1845, the British mathematician and astronomer John Couch Adams communicated his preliminary calculations on position of the perturber that was upsetting the orbit of Uranus to Cambridge Observatory Director James Challis and Astronomer Royal George Airy. Challis was unimpressed by the calculations and did nothing. The prediction languished, untested. A year later, the French mathematician Urbain Le Verrier published his prediction of the position of the perturbing body. Airy, hearing of this confirmation of Adams's result, initiated observations at Cambridge. Meanwhile, French astronomers contacted by Le Verrier showed no interest in following up his predictions. So in Sept. 1846, Le Verrier contacted Johann Galle at the Berlin Observatory who on his first night of observation after receipt of Le Verrier's letter observed Neptune within 1 deg of the predicted position (and 12° away, it later turned out, from Adams's prediction). Arguments over precedence for the prediction and subsequent discovery resulted in over 30 years of bitterness between France and British astronomers.

In this story we see the competition between British and French theoreticians, the goad of competition awakening interest in the British scientific establishment, and the cooperation between a French theoretician and a German observer. *Plus ça change, plus c'est la même chose*. The modern search for exo-planets offers many examples where competition drives innovation and collaboration expands opportunities. The steady advance in the precision of radial velocity (RV) measurements is an excellent case in point with initial discoveries of 51 Peg and other planets being made at the 10s of m s^{-1} level [27, 24] to the present day where observers routinely achieve 1-2 m s^{-1} accuracy [22, 15]. On the drawing boards are still more precise measuring engines with a laser comb reference [20] potentially capable of cm s^{-1} accuracy and new spectro-interferometers with infrared or multi-object capability [21, 13]. The cooperation between radial velocity and transit observers highlights the importance of working together to come up with striking new results [11], e.g. determining the density of a transiting planet from its mass (RV) and radius (transit).

However, as projects become larger than individual groups or even countries can reasonably afford, collaboration becomes a necessity. We have many wonderful examples of such collaborations: the Hubble and James Webb Space Telescopes; the Akari, Herschel and Planck infrared missions; and the ALMA millimeter array. These large projects plus smaller joint efforts on instruments or sharing of telescope time provide encouraging examples of collaboration enabling our most ambitious endeavours.

Finally, I note the importance of the third “C", “Coordination," which must mediate between collaboration and competition. Conferences like this one at the scientist-to-scientist level and high level meetings between funding agencies help to ensure that scarce resources are applied thoughtfully to address key scientific questions. The Terrestrial Planet Finder (TPF) program has had a decade of such meetings to make sure that appropriate intermediate steps are taken toward our goals of detecting other Earths and searching for life. The discussions are less about individual projects and more about making sure the goals are well defined and the technology efforts well planned so that when a major mission is executed, the world’s resources are carefully allocated.

COMPETITION BETWEEN GROUND AND SPACE

In a perfect world there would be little competition between ground and space efforts. The expense of a space project is so great and its timescale for implementation so long that one should always adhere to the adage that "If it can be done from the ground, it will be done from the ground long before it can be done from space." A scientific question important enough to merit a billion dollars or more on a space project can always attract enough ground based resources for an *adequate* solution in the 10-15 years it takes to develop a space mission. The project might not be done as well or as cleanly as from space, but the major result will be understood if a ground-based attack can be mounted. Thus it is critical to identify the domains uniquely suited to ground and space. I discuss this concept in the context of two areas of exoplanet research: indirect and direct detection of gas giant and terrestrial planets.

Indirect Evidence for Earth-like Planets in the Habitable Zone

The trade-off between ground and space is under intense review at the present time as the scientific community weighs the importance of an astrometric mission similar

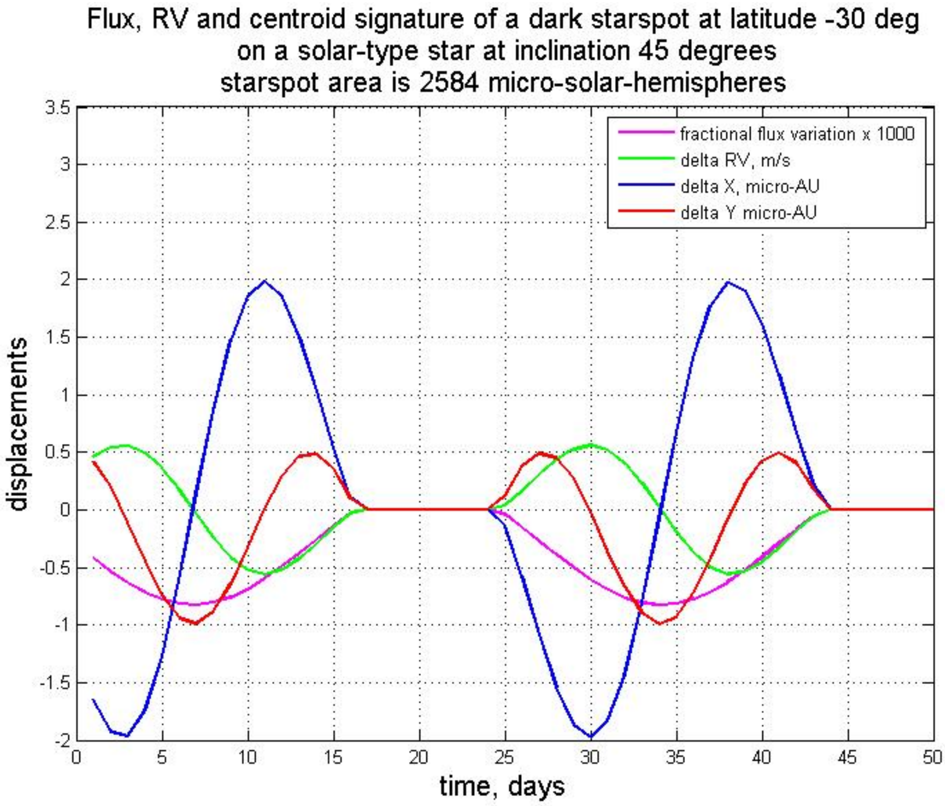

FIGURE 1. A simple model of a starspot traversing the face of a star predicts roughly 0.5 m s^{-1} of radial velocity noise (1σ) and 0.25 μas (1σ) of astrometric jitter for a star at 10 pc. Starting at the extreme left, from bottom to top the curves are: ΔX (AU, blue), $1000\times(\Delta Flux/Flux,$ purple), ΔY (AU, red), ΔRV (m s^{-1}, green). Courtesy J. Catanzarite.

TABLE 1. Radial Velocity and Astrometric Searches for Earth-Analogs

	Astrometry	Radial Velocity
Starspot Noise (1σ, τ =2 week)	0.25 (μas)	0.5 (m s^{-1})
Earth/Sun Analog at 10 pc	0.3 (μas)	0.09 (m s^{-1})
# Epochs for SNR=5.8	40	1,000
Duration	1 yr	40 yrs

to the Space Interferometer Mission (SIM-Lite; Unwin et al 2008) to find potentially habitable terrestrial planets (1-5 $M_\oplus$) orbiting nearby solar type stars. These planets will someday be the targets of direct imaging systems which will look for markers of an atmosphere (CO_2 and H_2O) and even of primitive life itself (such as O_3 and O_2; Beichman et al. 2007). As mentioned above, the radial velocity technique has made great strides in sensitivity and is close to breaching the 1 m s^{-1} precision barrier. Will this be enough to reach habitable terrestrial planets or will another technique such as astrometry be needed?

TABLE 2. Nominal yield for 40% of SIM Lite devoted to exoplanet survey

Mass Sensitivity at mid-habitable zone	1 $M_\odot$	2 $M_\odot$	3 $M_\odot$
Number of Targets Surveyed	69	160	259

The RV signature of a 1 $M_\oplus$ planet orbiting a G star at 1 AU is 0.09 m s^{-1}, independent of distance to the star. The comparable astrometric signature for a star at 10 pc is 0.3 μas. While RV instrumental sensitivity is improving rapidly, it is becoming apparent that the limit to RV precision is not instrumental (given access to enough time on large telescopes) but the stars themselves.

Consider a starspot covering approximately 0.1% of the solar hemisphere, a typical value for the Sun. Depending on the orientation with respect to the line of sight, such a spot would cause roughly a 0.5 m s^{-1} variation in the measured Doppler velocity and a 0.25 μas variation in position for a star at 10 pc (Figure 1). The effects, of course, are more complex with granulation and other photospheric phenomena being particularly important for RV observations which depend on the measurement of line profiles. Astrometric observations are made in white light and are immune to some of these effects. This simple analysis is confirmed by careful analysis of RV measurements for stars without planets which indicate that that majority of stars (perhaps more than 80%) have RV “jitter" as large as 1-3 m s^{-1} [15]. The CoRoT satellite will shortly provide data to address whether the majority of dwarf stars are as noisy or noisier than the sun [1, 5].

To average a σ =0.5 m s^{-1} single measurement accuracy down to the $S = 0.09/SNR$ cm s^{-1} precision needed for accurate detection (Signal to Noise Ratio, SNR=5.8; Traub et al 2009) would require a duration of $(SNR \times \sigma/S)^2 \times \tau$ or more than 40 years where $\tau \sim 2$ week is coherence time of the noise source, or roughly the average lifetime of a starspot (Table 1). A comparable analysis is more encouraging for astrometric detections [36]. The comparable single measurement accuracy is $\sigma = 1\,\mu$as with a stellar jitter of $< 0.05\,\mu$as. Averaging down the instrumental noise to achieve SNR=5.8 on an Earth analog orbiting a G star at 10 pc would take only one year. More detailed examinations of the RV vs. astrometric comparison are now underway, but the conclusion is becoming clear that for the vast majority of stars which are as active or more active than the sun, RV jitter will preclude the detection of habitable zone earths except, perhaps, for M stars. Space astrometry with SIM-Lite accuracy will be a necessity to achieve this goal. Table 2 indicates that by using 40% of the available mission time, SIM-Lite could measure between 70 and 260 stars to the precision needed to find 1-3 $M_\oplus$ planets in the habitable zones of their parent stars.

IMAGING PLANETS DIRECTLY

Observing Planets from the Ground

The number of directly imaged planets has more than doubled within the past six months, with 4 objects being detected around two nearby, young A stars. Because the 3 planets around HR8799 [26] and the single planet around Fomalhaut [16] are young, their internal reservoirs of gravitational energy generate enough luminosity to make the objects visible [31]. Stars older than about 100 Myr soon fade into obscurity and by 1 Gyr are invisible with existing coronagraphic capabilities. These young planets plus two earlier discoveries, 2M1207 [8] and GQ Lup [28], are confirmed to be companions via their common proper motion with their host star and in the case of Fomalhaut-b by orbital motion as well. What remains controversial, however, is the identification of these objects as planets ($<$13 M_{Jup}, the deuterium burning limit), as opposed to brown dwarfs ($13 < M < 70$ M_{Jup}) or even low mass stars ($>$70 M_{Jup}). The relations between near-IR brightness, age, and mass are quite uncertain and dynamical mass determinations are impractical for objects on long period orbits. In fact, the models for young stars have been called into direct question. Marley et al (2007) argued that core accretion models predict brightness levels 5-30 times lower at a given age than models that simply follow the luminosity evolution of a pre-existing ball of gas. What is missing to resolve this controversy are objects of known age for which a combination of imaging (giving luminosity, effective temperature) plus dynamical information (giving mass) is available to anchor the models. These combined data may become available with a combination of imaging using interferometers (Keck-I or VLT-I), coronagraphic imaging with ground-based telescopes or JWST, and dynamical mass measurements from ground-based RV or space-based astrometry using SIM-Lite [3, 33].

Contrast ratio levels detectable with Adaptive Optics on 5-10 m telescopes are approaching $10^{-4} - 10^{-5}$ at $1''$ which corresponds to 10s of AU for nearby young stars. There are prospects for 1-2 orders of magnitude improvement in limiting contrast over the next few years as new instruments such as the Gemini Planet Imager (GPI; Macintosh et al 2007), P1640 at Palomar (Oppenheimer and Hinckley 2009) and Sphere for the VLT come into operation. With coronagraphs on extremely large, diffraction limited telescopes (30-42 m), it should be possible to image young (10-100 Myr), gas-giant planets orbiting within 2-3 AU of the closest young stars (25-50 pc), and possibly even detect mature planets orbiting the nearest, low mass stars ($<$5 pc) where the contrast ratio is favorable, e.g. GL 876 and GL 3522. See figure 2 and the discussion below.

Observing Giant Planets with JWST

While the James Webb Space Telescope (JWST) has a diameter of "only" 6.5 m compared with existing 8-10 m telescopes and planned 30-42 m telescopes on the ground, and while the JWST's wavefront error is relatively coarse, $\sim$130 nm, compared with the wavefront errors $<$50 nm possible with extreme AO systems on the ground, JWST is a cooled telescope operated in an extremely stable space environment. JWST will have

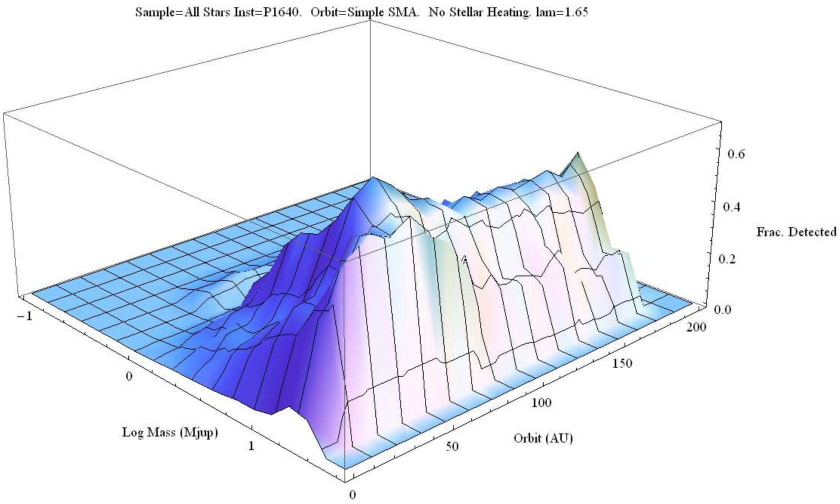

FIGURE 2. A Monte Carlo simulation shows the fraction of planets of a given mass and age orbiting a sample of 650 young stars that were detectable using the Lyot coronagraph on the P1640 instrument at 1.6 μm.

enormous sensitivity at exactly the wavelengths where young planets are predicted to be very bright, i.e. at 4-5 μm where the transparency of their atmospheres allows radiation from hot interior levels to emerge [2, 6, 7]. The three imaging instruments on JWST each have a coronagraphic capability: NIRCam has a traditional Lyot coronagraph [18] operating from 2- 5 μm; the Canadian Tunable Filter Imager [9] has a traditional Lyot coronagraph plus an innovative non-redundant mask imaging capability at 3-5 μm [32]; the mid-IR instrument, MIRI [30] has Four Quadrant Phase Masks operating around 10 μm. JWST should be able to observe planets more massive than 0.1M_{Jup} outside $1''$ with its Lyot coronagraphs and planets more massive than 1 M_{Jup} inside $1''$ with its NRM interferometric mode.

Figure 3 and Figure 2 show the fractional yield of a ground-based instrument (P1640 at Palomar) and a space-based instrument (the NIRCAM coronagraph on JWST) surveying a sample of 650 young stars (Beichman et al 2009, in preparation). In this Monte Carlo simulation, planets of various masses (0.1-40 M_{Jup}) were placed at distances between 0.5-200 AU from the star. The brightness of the planet was taken from models appropriate to the planet's mass and the age of the host star [2]. The average planet detected by JWST has a mass of 2 M_{Jup} with an age of 70 Myr and located at 130 AU. There is a long tail of detections of planets with masses as low as 0.1 M_{Jup} for the closest stars. Comparable values for the ground-based search with P1640 at Palomar is an average mass of 8 M_{Jup} with an age of 10 Myr and located at 110 AU. There is a long tail of detections for planets within than 50 AU for the closest stars. Detection of these planets will test the efficacy of disk fragmentation mechanisms for the formation of gas giant planets [10]. Spectroscopy of these systems will help to assess their physical properties. A separate analysis shows that JWST, but not ground based telescopes, will be able to find 1-2 Gyr, 1 M_{Jup} gas giants around the nearest M stars.

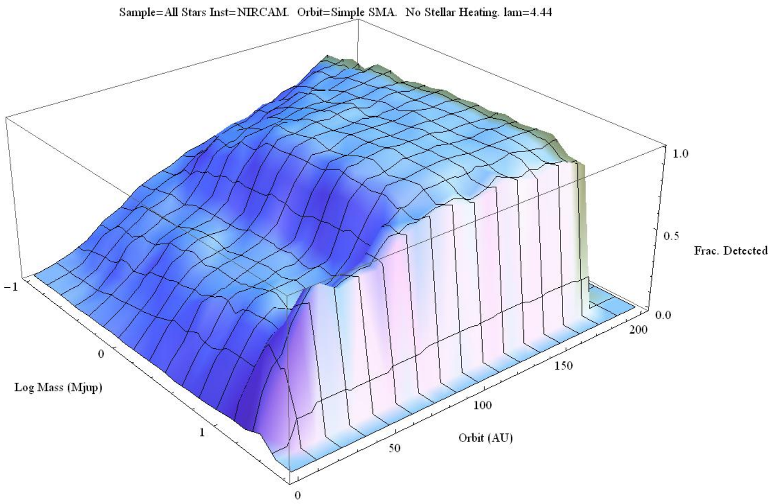

FIGURE 3. A Monte Carlo simulation shows the fraction of planets of a given mass and age orbiting a sample of 650 young stars that were detectable using the Lyot coronagraph on JWST's NIRCam instrument at 4.4 μm.

Imaging Terrestrial Planets

The previous section demonstrates that both ground-based facilities and JWST will be challenged to study young, gas giant planets. Neither is capable of the much more demanding task of detecting and characterizing Earth analogs orbiting nearby stars. While transit observations may enable direct detection of some "Super Earths" ($\sim$2 $R_{\oplus}$) orbiting M stars [12, 17], the general task of direct imaging will require space telescopes of exquisite precision: an ultra-high contrast coronagraph operating on a $>$ 4 m visible light telescope, a nulling interferometer operating over a $50-100$ m baseline in the mid-infrared, or a 50 m diameter occulter operating tens of thousands of km in front of a 4 m telescope (TPF-C, TPF-I, or TPF-O, respectively). For details the reader is referred to the proceedings of a recent conference (http://exep.jpl.nasa.gov/exep_exForum.cfm) and community report [19] on exoplanet missions.

CONCLUSIONS

Competition, collaboration and coordination form the cornerstones of progress in most human endeavors. Exoplanet research is no exception. Competition serves as a spur to innovation and rapid progress. Collaboration serves to allocate intellectual and financial resources efficiently for projects larger than what a small group can comfortably undertake. And coordination through frequent meetings such as these ensures an appropriate balance between competition and collaboration. This philosophy has brought us great successes, from HST to Herschel/Planck, and promises to to so in the future with JWST and ALMA. In the long term, we hope that many of the participants of this conference will help implement a mission that will find and characterize Earth analogs and search for life on other worlds.

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