Discovering Worlds in Transit

Astronomers are finally on the cusp of finding planets like ours.

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As an extrasolar planet hunter, you can’t afford to be timid or meek; you’ve got to be willing to stick your neck out. In fact, just in the last six months, more than half of all previously known extrasolar planets (approximately 50) have been called into question by new astrometric observations of their parent stars (see sidebar **name and pg TK**). What’s more, a hot astronomical debate erupted after the word "planet" was attached to the discovery of 18 wandering objects weighing several Jupiter masses in Orion’s Sigma Orionis star cluster (see "Lonely, Dim Objects Spark Big Debate," AstroNews, February 2001).

To stay on top of their game, planet hunters need to be sure that the search methods they employ are state−of−the−art. Unfortunately, the standard workhorse method for detecting extrasolar planets − through the Doppler signature, or wobble, produced on the spectra of the stars they orbit − is reaching its limits. Even with the best detectors and largest telescopes in the world, Earth−sized planets − the Holy Grail of the planet−hunting universe − continue to elude those who employ this "radial velocity" technique.

The radial velocity method provides only the velocity of the star toward or away from an observer. It can’t resolve the true, three−dimensional direction of the wobble caused by an orbiting planet. Consequently, the radial velocity method only measures a minimum possible mass for suspected extrasolar planets. And only when astronomers are certain of the inclination of the orbit can they determine a planet's true mass.

To find elusive, Earth−like worlds, astronomers will need to adopt novel and clever detection methods that possess the sensitivity necessary to record the subtle orbital effects of an Earth−sized planet. This is the story of how one new extrasolar planet hunting technique − called the Photometric Transit Method (PTM) − is showing significant promise in the search for distant Earth−like worlds.

We are a group of astronomers, working at various observatories around the world, who have conspired to continuously search for transit events with the hope of discovering potentially habitable − a term generally reserved for planets with an ability to maintain surface water − Earth−like planets. Now, thanks to the dubious alliance of a giant planet orbiting the star HD 209458 and a little binary star system called CM Draconis, we're well on our way to finding just what we've been looking for. In fact, we've employed PTM to discover what may be the first Earth−like planet outside of our solar system in CM Draconis.

HD209458: A Glimmer of Hope

On November 7, 1999 HD 209458 dimmed slightly and subsequently rebounded to full brightness over the course of a few hours. Analysis from the November observation, as well as subsequent observations of HD 209458, confirms that the astronomers witnessed, for the first time outside of our solar system, the direct effects of a planet crossing the face of a star − an event known as a planetary transit.

As it turns out, two independent teams of astronomers had suspected, from earlier Doppler measurements, that a Jupiter−sized planet was orbiting HD 209458 at a distance one−twentieth the separation between Earth and the sun.

And because the planetary companion to HD 209458 was so close to its parent star, the likelihood that it might actually pass right in front of HD 209458 was rather high − about 10 percent**.** In general, it is quite unlikely that an extrasolar planet’s orbit will be favorably aligned to produce regular transit events. For example, an average extraterrestrial astronomer only has about a one percent chance of seeing Earth transit our sun.

Since the planet orbiting HD 209458 was observed to cross almost directly in front of the star’s disk, its orbit must be very close to edge−on − perpendicular to the plane of the sky seen from our vantage point on Earth. Such an orbital configuration is valuable to astronomers because it allows them to place tight constraints on the parameters of the system. In fact, from that single event, which dimmed the light of HD 209458 by a paltry 2 percent, astronomers were able to determine the size (about one third larger than Jupiter), the mass (about two thirds the mass of Jupiter), and the density (one third the density of liquid water, something like that of a sponge cake) of the giant planet (see "Planet Caught Crossing Face of Distant Star," AstroNews, February 2000). Previously, astronomers were only able to determine simple orbital parameters and place a lower limit on the mass of the planet.

Due to the decreasing cost and increasing availability of Charge Coupled Device (CCD) cameras, the photometric transit method also enables amateur astronomers to detect extrasolar planets around nearby bright stars. The drop in brightness caused by giant planets − such as the one around HD 209458 − can be as much as 2 percent, well within reach of a CCD camera on a small telescope under a fairly dark sky. With a modest investment, amateur astronomers can hone their planet−searching techniques on HD 209458 (see "Find an Extrasolar Planet,"**pg Tk**).

Improving the Odds

There are several things that astronomers can do to increase their chances for actually discovering planets through transit events. First, one can observe a very large number of stars in the hope that at least a few will display transits. Simply due to chance, at least a few percent of extrasolar planets should have edge−on orbits. Indeed, several proposed space missions, such as the Kepler mission (led by William Borucki of NASA's Ames Research Center) and the European COROT mission, as well as a number of ground−based programs, are taking this wait−and−see approach.

One may exclusively observe star systems where a planet's orbit is almost sure to be edge−on as Jean Schneider and Michel Chevreton of the Observatoire de Meudon in Paris first suggested. For example, planets orbiting double star systems called eclipsing binary systems are likely to have edge−on orbits. That's because planets circling both components of a double star system should be flattened down into the orbital plane of the companion stars. Moreover, modern computer simulations indicate that planets can exist in stable orbits around close double stars as long as the planets are at least three times farther away from the stars as the stars are separated from each other.

Eclipsing binary star systems, of which thousands are known (such as CM Draconis), are fundamentally important to astronomy as almost all direct stellar diameter and stellar mass measurements have been gleaned from observations of such systems. In these systems, the companion stars orbit a common center of mass in an edge−on orbit, so that they regularly eclipse each other. Two eclipses occur every orbital period as each star, in turn, passes in front of the other.

Waiting for the Double Dip

Any planet orbiting in the plane of an eclipsing binary will transit twice with each orbit. So astronomers searching these systems for transits look for a characteristic double dip, as the planet crosses one star and then the other. Moreover, as the planet transits the system, the two stars are rapidly orbiting each other. This causes the transits to occur much more rapidly (less than an hour in duration each) than they would if the planet were moving across a single star. For example, an extraterrestrial astronomer would see that it takes Jupiter more than a day to transit the sun.

Another advantage is that stars in close eclipsing binary systems are tidally locked in rotation. In other words, the two stars always face toward each other, similar to the way the moon always shows the same face toward Earth. This means astronomers won’t mistake dark starspots on the stellar surfaces for planetary transits because the starspots will appear and disappear with the known orbital period of the two stars around each other.

A survey of brightness variations in eclipsing binary systems with planets should exhibit regular stellar eclipses along with the much smaller semi−regularly recurring transits that can be matched to a given planetary orbital period. Transit events around eclipsing binaries are thus termed "quasi−periodic" − they occur at predictable but irregular time intervals.

CM Draconis: A Case for Earth−like Worlds

To further maximize the chances for success, our research collaboration (called the TEP [Transit of Extrasolar Planets] Network) selected CM Draconis, one of the smallest known eclipsing systems, to lead the search for potentially habitable planets in eclipsing binary systems. Two red dwarf stars (spectral class M4), which orbit each other every 1.26 days, make up the CM Draconis binary. As each star is only about one−quarter the diameter of the sun, the stars’ combined area only accounts for about 12 percent of the sun’s disk area. This combination makes the CM Draconis system an ideal location to begin our search because Earth−like planets are easier to detect around small stars than large stars (see

"Size Matters," page **TK**). In fact, an Earth−sized planet would produce a brightness drop in the bantam CM Draconis system about 8.3 times larger than if it were crossing the face of the sun.

Members of the TEP Network observed CM Draconis for more than 1,000 hours from New York, New Mexico, California, South Korea, Russia, Greece, France, and the Canary Islands between 1994 and 1999. And we've just completed follow−up observations on two possible planetary candidates (with orbital periods of 20 and 27 days). Our analysis of the data shows that if any of these small dips in the brightness of the CM Draconis system are actually caused by a transiting planet, then the planet must be quite small − only 2.4 Earth−diameters in size. Indeed, this is much smaller than the giant extrasolar planets so far discovered with the "radial velocity" method.

Because the two stars of the CM Draconis system (named A and B) are so dim (about 1.03 percent the brightness of the sun), any planets around these stars with orbital periods from about 18 to 35 days would receive about as much light from both stars as Earth and Mars each receive from our sun. Thus, by current definitions of habitability, any candidate planets would be small enough and at the right distances to be potentially habitable. Although there may also be giant planets circling the CM Draconis system, several dozen eclipse measurements show that there cannot be any planets more massive than 1.5 times Jupiter's mass with orbital periods less than 6 years.

Checking All Possibilities

To calculate unambiguous brightness changes in the CM Draconis system, we took CCD exposures of CM Draconis as well as several nearby stars that don't vary in luminosity. We call these stars "standard stars." Although all the stars in an image will vary in brightness due to fluctuations in Earth's atmosphere, they should all vary in about the same way within a given image. By subtracting the brightness of the standard stars from that of CM Draconis, we could measure how much its brightness changed compared to the standard stars.

One way to tell if a drop in brightness is due to a real planetary transit or something else − like a flickering in Earth’s atmosphere − is to see if the times of the transits are consistent with the orbital parameters of a potential planet. Nonetheless, many possible planet orbits could produce transit features. Which of those fit the drops in the light curve at the right locations? To answer this question we had to test planet models with various orbital periods as well as locations in their orbits (called the orbital phase) to find those that matched the observed drops in the CM Draconis system.

And the Winners Are ?

Our algorithm picked out nine possible planets that could account for the brightness dips in CM Draconis. Some would produce more dips than others − the number of dips in brightness (i.e., suspected transit events) ranged from 5 to 11, depending on the planet model. But all the dips were quite small, indicating that only planets smaller than about 2.5 Earth−radii could be present. A transiting planet as large as 3 Earth−radii would have required only one transit to be noticed by our algorithm. Still, these nine candidates needed observational confirmation before declaring them full−fledged planets.

So, we went back to the observatory hoping that the brightness of CM Draconis would drop again at the exact times predicted by the models. This was the only sure way to confirm or rule out the nine remaining planetary candidates. In 1999, we observed CM Draconis at a number of predicted transit times for seven of these nine candidate planets.

After searching for hundreds of millions of possible transiting planets with periods from 7 to 60 days, we’ve narrowed the field to two planetary candidates in CM

Draconis. Both candidates (if they prove to be planets) lie within the habitable zone of the CM Draconis system. Moreover, the candidates are small enough to be large terrestrial planets (although their densities will remain unknown until their masses are measured). And by the end of this year we will likely know if either of these candidates is a planet.

The photometric transit method currently shows the most promise for discovering extrasolar, Earth−size planets. Within the next decade, several spacecraft and many ground−based projects will continue to use this method to search for, and likely find, many potentially habitable extrasolar planets. These are extremely exciting times for planet hunters. We are finally on the verge of answering the most intriguing question in planetary science: "Is there another place like home?"

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Sidebar: Size Matters: Why CM Draconis?

The likelihood that a planet will have such an edge−on orbit so as to cross our line−of−sight depends mostly on the distance of the planet from its star, but also somewhat on the size of the star as well. The closer the planet is, the larger it’s angular size will be relative to its parent star. In addition, the smaller the parent star is, the smaller the planet that may be detected through the photometric transit method. That’s because a planet of a given size will block a proportionately larger part of a small star's disk as opposed to a large star's disk, making it easier for instruments to detect.

Sidebar: Find an Extrasolar Planet

If you have a small telescope equipped with a CCD camera, a photoelectric photometer, or even a stand alone CCD camera by itself, you can detect the transit of a giant planet across the star HD 209458 (visual magnitude 7.65, right ascension 22h03m10.77s, declination 18°53'03.5"). To do so, you will need a camera that can discern a 2−percent drop in the relative brightness of this star compared to nearby stars in the field of view (you may have to measure the brightness of several nearby stars and add them up before you compare them with the brightness of HD 209458).

The table is an ephemeris of the mid−times for upcoming transits. Transits will start about 1 1/2 hours before this time, and end about 1 1/2 hours after this time. Times are given in Universal Time (UT) for transits events that occur 30° or more above the local horizon (mean U.S. latitudes and mean latitude for southern Europe). Subtract 7 hours for Pacific Daylight Time (PDT), 4 hours for Eastern Daylight Time (EDT), add 1 hour for Central Europe Time (CET), and add 9 hours for Japan Standard Time (JST). Remember that this time correction may place the observation on the preceding day (i.e., before midnight) for U.S. observers.

Upcoming Planetary Transits of HD 209458 for Year 2000:

Month	Day	Hour	Minute	Location	Altitude
8	2	2	59	east US	39
				Europe	57
8	5	15	34	Japan	73
8	9	4	10	east US	57

				Europe	41
8	12	16	46	Japan	68
8	16	5	21	west US	46
				east US	68
8	19	17	57	Japan	50
8	23	6	32	west US	62
				east US	63
8	30	7	44	west US	69
				east US	47
9	2	20	19	Europe	46
9	6	8	55	west US	57
9	9	21	31	Europe	60
9	13	10	6	west US	40
				Japan	42
9	16	22	42	Europe	63
9	20	11	17	Japan	61
9	23	23	53	east US	43
				Europe	54
9	27	12	29	Japan	74
10	1	1	4	east US	60
				Europe	37
10	4	13	40	Japan	64
10	8	2	16	west US	50
				east US	69
10	11	14	51	Japan	45
10	15	3	27	west US	65
				east US	60
10	22	4	38	west US	67
				east US	43
10	29	5	49	west US	54
11	1	18	25	Europe	62
11	5	7	1	west US	35
11	8	19	36	Europe	62
11	15	20	47	Europe	50
11	19	9	23	Japan	74
11	22	21	59	Europe	33
11	26	10	34	Japan	60
11	29	23	10	east US	68
12	3	11	45	Japan	40
12	7	0	21	east US	56
12	14	1	32	east US	38
12	21	2	44	west US	50
12	28	3	55	west US	31