Theoretical Models of Extrasolar Giant Planets

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The recent discoveries of giant planets around nearby stars has galvanized the planetary science community, astronomers, and the public at large. Since direct detection is now feasible, and is suggested by the recent acquisition of Gl229 B, it is crucial for the future of extrasolar planet searches that the fluxes, evolution, and physical structure of objects from Saturn’s mass to 15 Jupiter masses be theoretically investigated. We discuss our first attempts to explore the characteristics of extrasolar giant planets (EGPs), in aid of both NASA’s and ESA’s recent plans to search for such planets around nearby stars.

1. Introduction

After years of obscurity in the backwaters of astronomy, the recent epochal detections of giant planets around nearby stars has put the search for extrasolar planets on its center stage. The discoveries of 51 Peg B [1], τ Boo B, 55 Cnc B and C, 70 Vir B, and 47 UMa B [2–4], and the belated recognition that HD114762 [5] is in this class have galvanized the planetary science community, astronomers, and the public at large. Table 1 lists these newly–discovered planets, in order of increasing semi–major axis, along with the giant planets in our solar system and the brown dwarf Gl229 B [6]. Also shown are $M_p \sin(i)$, orbit period, eccentricity, distance to the sun, estimated surface temperature, and age (when an age could be comfortably assigned). The wide range in mass (0.5 $M_J$ to $\sim 10 M_J$) and period (3.3 \textit{days} to $\sim 20 \text{ years}$), as well as the proximity of many of the planets to their primaries, was not anticipated by most planetary scientists. Though the technique of Doppler spectroscopy used to find most of these planets selects for massive, nearby objects, their variety and existence is a challenge to conventional theory.

Within the last year, building upon our previous experience in the modeling of brown dwarfs and M stars, we published theoretical studies on the evolution and spectra of extrasolar giant planets (EGPs\textsuperscript{1}) (Burrows et al. [7]; Saumon \textit{et al.} [8]; Guillot \textit{et al.} [9]; Marley \textit{et al.} [10]).

Brown dwarfs ($< 0.08 M_\odot$) are transition objects that straddle the realms of planets and stars, have atmospheres composed of a complex soup of molecules and grains, and can achieve central temperatures adequate to consume their stores of cosmological deuterium, while inadequate to ignite sufficient light hydrogen to avoid cooling into obscurity within a Hubble time. Nevertheless, they are characterized by straightforward extensions of the same equation-of-state (EOS) and atmospheric physics appropriate for the less massive giant planets.

Some of the space platforms and new ground–based facilities that have or will obtain relevant infrared and optical data include the HST (WFPC2, NICMOS), the IRTF, the MMT 6.5–meter upgrade, the Large Binocular Telescope (LBT) (planned for Mt. Graham), Keck’s I and II (with HIRES), the European ISO, UKIRT, and

\textsuperscript{1}We use this shorthand for \textit{Extr}asolar \textit{G}iant \textit{P}lanet, but the terms “exoplanet” or “super–jupiter” are equally good.

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Table 1

The Giant Planet Bestiary

<table>
<thead>
<tr>
<th>Object</th>
<th>Star</th>
<th>Mass (M_J)</th>
<th>a (A.U.)</th>
<th>P (days)</th>
<th>e</th>
<th>T_eff (K)</th>
<th>D (pc)</th>
<th>Age (Gyrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ Boo B</td>
<td>F7</td>
<td>&gt; 3.87</td>
<td>0.046</td>
<td>3.313</td>
<td>0.0</td>
<td>1500</td>
<td>19</td>
<td>?</td>
</tr>
<tr>
<td>51 Peg B</td>
<td>G2.5</td>
<td>&gt; 0.46</td>
<td>0.05</td>
<td>4.23</td>
<td>0.0</td>
<td>1250</td>
<td>15.4</td>
<td>8</td>
</tr>
<tr>
<td>υ And B</td>
<td>F8</td>
<td>&gt; 0.6</td>
<td>0.057</td>
<td>4.61</td>
<td>~0.03</td>
<td>1350</td>
<td>16.1</td>
<td>?</td>
</tr>
<tr>
<td>55 Cnc B</td>
<td>G8</td>
<td>&gt; 0.8</td>
<td>0.1</td>
<td>14.76</td>
<td>0.0</td>
<td>1000</td>
<td>13.5</td>
<td>?</td>
</tr>
<tr>
<td>HD114762 F8</td>
<td>&gt; 0.46</td>
<td>0.05</td>
<td>4.23</td>
<td>0.0</td>
<td>1250</td>
<td>15.4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>70 Vir B</td>
<td>G4</td>
<td>&gt; 6.6</td>
<td>0.45</td>
<td>116.6</td>
<td>0.40</td>
<td>380</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>47 UMa B</td>
<td>G0</td>
<td>&gt; 2.39</td>
<td>2.11</td>
<td>3 yrs</td>
<td>~0.03</td>
<td>180</td>
<td>12</td>
<td>6.9</td>
</tr>
<tr>
<td>Gl411 B (?)</td>
<td>M2</td>
<td>~0.9</td>
<td>2.33</td>
<td>5.8 yrs</td>
<td>?</td>
<td>100</td>
<td>2.52</td>
<td>?</td>
</tr>
<tr>
<td>55 Cnc C</td>
<td>G8</td>
<td>&gt; 5</td>
<td>5–10</td>
<td>15–20 yrs</td>
<td>?</td>
<td>175</td>
<td>13.5</td>
<td>?</td>
</tr>
<tr>
<td>Jupiter</td>
<td>G2</td>
<td>1.0</td>
<td>5.2</td>
<td>11.86 yrs</td>
<td>0.048</td>
<td>125</td>
<td>–</td>
<td>4.6</td>
</tr>
<tr>
<td>Saturn</td>
<td>G2</td>
<td>0.3</td>
<td>9.5</td>
<td>29.46 yrs</td>
<td>0.056</td>
<td>95</td>
<td>–</td>
<td>4.6</td>
</tr>
<tr>
<td>Gl229 B</td>
<td>M1</td>
<td>30–55</td>
<td>&gt; 44.0</td>
<td>&gt; 400 yrs</td>
<td>?</td>
<td>960</td>
<td>5.7</td>
<td>&gt; 1</td>
</tr>
</tbody>
</table>

SIRTF, along with a large number of medium–to large–size telescopes optimized or employed in the near–infrared. One project of Keck I and II, under the aegis of NASA’s ASEPS-0 (Astronomical Study of Extrasolar Planetary Systems) program, will be to search for giant planets around nearby stars. A major motivation for the Palomar Testbed Interferometer (PTI) supported by NASA is the search for extrasolar planets. Recently, Dan Goldin, the NASA administrator, outlined a program to detect planetary systems around nearby stars that may become a future focus of NASA. This vision is laid out in the Exploration of Neighboring Planetary Systems (ExNPS) Roadmap (see also the “TOPS” Report [11]).

2. Early Calculations of the Evolution and Structure of Extrasolar Giant Planets

Our group [7,8] recently calculated a suite of models of the evolution and emissions of EGPs. Surprisingly, no one had accurately mapped out the properties of objects between the mass of giant planets in our solar system and the traditional brown dwarfs (\( \geq 10^{-20} M_J \), where \( M_J \) is the mass of Jupiter, \( \sim 10^{-3} M_\odot \)). This is precisely the mass range for the newly–discovered planets listed in Table 1.

EGPs will radiate in the optical by reflection and in the infrared by the thermal emission of both absorbed stellar light and the planet’s own internal energy. In Burrows et al. [7] we included the effects of “insolation” by a central star of mass \( M_* \) and considered semi-major axes \( (a) \) between 2.5 A.U. and 20 A.U. Giant planets may form preferentially near 5 A.U. [12], but as the new data dramatically affirm, a broad range of \( a \) can not be excluded. We evolved EGPs with masses \( (M_p) \) from 0.3 \( M_J \) (the mass of Saturn) through 15 \( M_J \). Whether a 15 \( M_J \) object is a planet or a brown dwarf is largely a semantic issue, though one might distinguish gas giants and brown dwarfs by their mode of formation (e.g. in a disk or “directly”). Physically, compact hydrogen-rich objects with masses from 0.00025 \( M_\odot \) through 0.25 \( M_\odot \) form a continuum. However, our EGPs above \( \sim 13 M_J \) do burn “primordial” deuterium for up to \( 10^8 \) years.

The evolution of the bolometric luminosity \( (L_{bol}) \) of our suite of EGPs orbiting 5.2 A.U. from a G2V star as calculated in Burrows et al. [7] is depicted in Figure 1. One is struck immediately by the high \( L_{bol} \)’s for early ages and high masses. That a young “Jupiter” or “Saturn” will be bright has been known for some time, but ours are the first detailed calculations for objects with \( M_p > M_J \) and ages, \( t \), greater than \( 10^7 \) years. Below about 10 \( M_J \), \( L_{bol} \) is very roughly proportional to \( M_p^\alpha/t^\beta \), where \( 1.6 \leq \alpha \leq 2.1 \) and \( 1.0 \leq \beta \leq 1.3 \). An EGP with a mass of 2 \( M_J \) at age \( 10^7 \) years is two thousand times brighter than...
Figure 1. Bolometric luminosity ($L_{bol}$) in solar units of a suite of EGPs placed at a distance of 5.2 A.U. from a G2 V star versus time ($t$) in Gyr. The reflected luminosity is not included, but the absorbed component is. At $t \sim 0.2$ Gyr, the luminosity of the 14 M$_J$ EGP exceeds that of the 15 M$_J$ EGP because of late deuterium ignition. The data point at 4.55 Gyr shows the observed luminosity of Jupiter. The 0.3 M$_J$ EGP exhibits a strong effect of warming by the G2 V primary star at late stages in its evolution. Although this model resembles Saturn in mass, here it is placed at the distance of Jupiter from its primary. (The flattening in $L$ vs. $t$ for low masses and great ages is a consequence of stellar insolation.) The insert shows, on an expanded scale, the comparison of our lowest-mass evolutionary trajectories with the present Jupiter luminosity (from [7]).
the current Jupiter (and its \(T_{\text{eff}}\) is \(\sim 700\) K). At the age of the Pleiades (\(\sim 7 \times 10^7\) years), such an EGP would be \(\sim 200\) times brighter (with \(T_{\text{eff}}\) \(\sim 420\) K) and at the age of the Hyades (\(\sim 6 \times 10^8\) years) it would be \(\sim 18\) times brighter (with \(T_{\text{eff}}\) \(\sim 235\) K). The measured \(L_{\text{bol}}\) and \(T_{\text{eff}}\) of Jupiter are \(2.186 \pm 0.022 \times 10^{-9}\) \(L_\odot\) and \(124.4 \pm 0.3\) K, respectively [13]. At an age of 4.55 Gyr, our model of Jupiter has a luminosity of \(2.35 \times 10^{-9}\) \(L_\odot\) and an effective temperature of \(122\) K.

A few “facts” will serve to illustrate the mid-infrared character of massive young EGPs. Since the fluxes shortward of \(10\) \(\mu\)m (the N band) are generally on or near the Wien tail of the EGP spectrum, the fluxes in the near- and mid-infrared spectral bands increase even faster with mass and youth than \(L_{\text{bol}}\). In particular, if we assume that the emission is Planckian, that the orbital separation is \(5.2\) A.U., and that \(M_\star\) equals \(1.0\) \(M_\odot\), Jupiter’s N band flux would be \(\sim 8000\) times higher at age \(10^7\) years than it is now. At the age of our solar system, a \(2\) \(M_\odot\) EGP and a \(5\) \(M_\odot\) EGP would be \(\sim 6\) and \(\sim 90\) times brighter in the N band than the current Jupiter. Furthermore, in the M band (\(\sim 5\) \(\mu\)m), a \(2\) \(M_\odot\) EGP would be \(\sim 60,000\) times brighter at \(10^7\) years than the current Jupiter, but at \(10^9\) years “only” \(\sim 2.5\) times brighter than a coeval Jupiter. At the age of the Hyades, Saturn would be as bright as the current Jupiter. The fluxes due to the thermal emissions shortward of \(10\) \(\mu\)m of EGPs in the Pleiades (\(D \sim 125\) parsecs) would be greater than those from EGPs in the Hyades (\(D \sim 45\) parsecs), despite the latter’s relative proximity, because the Pleiads are younger (and, hence, at higher \(T_{\text{eff}}\)).

3. Giant Planets at Small Orbital Distances

It had been thought that the orbital radius of a giant planet had to be at least 4.0 A.U. [12], but the epochal detections of \(\tau\) Boo B, 55 Cnc B, and 51 Peg B belie this paradigm. Amazingly, 51 Peg B [1] is orbiting a G2.5 star, with a 4.23–day period, a semi-major axis of 0.05 A.U., an eccentricity near zero, and an inferred mass between 0.5 and 2 Jupiter masses.

One hundred times closer to its primary than Jupiter itself, 51 Peg B thwarts conventional wisdom. Boss [12] had argued that the nucleation of a H/He-rich Jovian planet around a rock and ice core could be achieved in a protostellar disk only at and beyond the ice point (at \(\sim 160\) K) exterior to 4 A.U. Walker et al. [14] had surveyed 21 G-type stars for reflex motion over 12 years, had detected none, and had derived upper limits of \(0.5–3\) \(M_\odot\) for the masses (modulo \(\sin(i)\)) of any planets interior to \(\sim 6\) A.U. that they may have missed. Zuckermann, Forveille, & Kastner [15] had measured CO emissions from a variety of near–T Tauri disks, had extrapolated to \(H_2\), and had concluded that there may not be enough mass or time to form a Jupiter around a majority of stars. The discoveries of 51 Peg B, \(\tau\) Boo B, and 55 Cnc B, while not strictly inconsistent with any of these papers, vastly enlarge the parameter space within which we must now search.

After 8 billion years (the estimated age of 51 Peg A), if 51 Peg B is a gas giant, its radius is only \(1.2 R_J\) (where \(R_J\) is the radius of Jupiter) and its luminosity is about \(3.5 \times 10^{-5} L_\odot\). This bolometric luminosity is more than \(1.5 \times 10^4\) times the present luminosity of Jupiter and only a factor of two below that at the edge of the main sequence. A radiative region encompasses the outer 0.03% in mass, and 3.5% in radius. Figure 2 from Guillot et al. [9] is a theoretical Hertzsprung-Russell diagram that portrays the major results of our 51 Peg B study. Depicted are \(L–T_{\text{eff}}\) tracks for the evolution of a \(1\) \(M_\odot\) gas giant and \(L\) for a \(1\) \(M_\odot\) “olivine” planet, all at a variety of orbital distances (indicated by the arrows). Also shown are the Hayashi track (boundary of the dark shaded region), the Hayashi exclusion zone (the dark shaded region itself), the Roche exclusion zone (the lightly shaded region), and the classical Jeans evaporation limit (dash-dotted line). The dotted lines on Figure 2 are lines of constant radius. The numbers on the tracks are the common logarithms of the ages in years. The study by Guillot et al. [9] demonstrated that 51 Peg B is well within its Roche lobe and is not experiencing significant photoevaporation. Its deep potential well ensures that, even so close to its parent, 51 Peg B is stable. If 51 Peg B were formed beyond
Figure 2. Hertzsprung-Russell diagram for 1 M$_J$ planets orbiting at 0.02, 0.025, 0.032, 0.05, and 0.1 A.U. from a star with the properties of 51 Peg A, assuming a Bond albedo of 0.35. Arrows indicate the corresponding equilibrium effective temperature. A Jupiter model is also shown, the diamond in the bottom right-hand corner corresponding to the present-day effective temperature and luminosity of the planet. Evolutionary tracks for planets of solar composition are indicated by lines connecting dots which are equally spaced in log(time). The numbers 7, 8, 9, 10 are the common logarithms of the planet’s age. Zero-temperature models for 1 M$_J$ planets made of olivine (Mg$_2$SiO$_4$) are indicated by triangles. The Hayashi forbidden region, which is enclosed by the evolutionary track of the fully convective model, is shown in dark grey. Models in the light grey region have radii above the Roche limit (and therefore are tidally disrupted by the star). The region where classical Jeans escape becomes significant is bounded by the dash-dotted line. Lines of constant radius are indicated by dotted curves. These correspond, from bottom to top, to radii (in units of R$_J$) in multiples of 2, starting at 1/4 (from [9]).
an A.U. and moved inward on a timescale greater than $\sim 10^6$ years, it would closely follow the $R_p \sim R_J$ trajectory to its equilibrium position.

For radiative/convective gas-giant models of 51 Peg B, the predicted radii after 1 Gigayear (Gyr) are between 1.35 $R_J$ and 1.9 $R_J$ for $M_p$'s from 2.0 $M_J$ to 0.5 $M_J$. These are as much as a factor of two smaller that the corresponding radii for fully convective planets. After 8 Gyr, the radii for these same planets are between 1.2 $R_J$ and 1.4 $R_J$. A giant terrestrial planet with a mass between 0.5 $M_J$ and 2.0 $M_J$ would have a radius between 0.31 $R_J$ and 0.35 $R_J$, three times smaller than that of a gas giant in the same mass range, and its corresponding luminosity would be an order of magnitude lower ($2.0 - 2.5 \times 10^{-6} L_\odot$). If photometry can be performed on 51 Peg B, $\tau$ Boo B, or 55 Cnc B, a measurement of bolometric luminosity will immediately distinguish the different models.


To constrain the properties of the brown dwarf Gl229 B [6, 16–18], we (Marley et al. [10]) recently constructed a grid of brown dwarf model atmospheres with $T_{\text{eff}}$ ranging from 600 to 1200 K and $100 < g < 3200$ m s$^{-2}$. We assumed a standard solar composition for the bulk of the atmosphere. Refractory elements (for example Fe, Ti, and silicates) condense deep in the atmosphere for $T_{\text{eff}} \approx 1000$ K, and thus have negligible gas-phase abundance near the photosphere, as is also true in the atmosphere of Jupiter. For an atmosphere similar to that of Gl229 B, chemical equilibrium calculations indicate that C, N, O, S, and P are found mainly in the form of methane (CH$_4$), ammonia (NH$_3$), water (H$_2$O), hydrogen sulfide (H$_2$S), and phosphine (PH$_3$), respectively. However, deep in the atmosphere, chemical equilibrium favors CO over CH$_4$ and N$_2$ over NH$_3$. Our model atmospheres incorporate opacities of these molecules, H$_2$, and He in their respective solar abundances and includes no other elements.

In Marley et al. [10], we employed a stellar evolution code and atmosphere models to estimate the physical properties of the brown dwarf, Gl229 B. By comparing our theoretical spectra with the UKIRT [17] and HST [18] data, we derived an effective temperature of $960 \pm 70$ K and a gravity between $0.8 \times 10^5$ and $2.2 \times 10^5$ cm s$^{-2}$. These results translate into masses and ages of 30–55 $M_J$ and 1–5 Gyr, respectively. As Figure 3 indicates, gravity maps almost directly into mass, and ambiguity in the former results in uncertainty in the latter. While the near infrared spectrum of Gl229 B is dominated by H$_2$O, we confirmed the presence of CH$_4$ in the atmosphere from our modeling of its features at 1.6–1.8 $\mu$m, 2.2–2.4 $\mu$m, and 3.2–3.6 $\mu$m. In addition, we found a flux enhancement in the window at 4–5 $\mu$m throughout the $T_{\text{eff}}$ range from 124 K (Jupiter) through 1300 K, and, hence, that this band is a universal diagnostic for brown dwarfs and planets. By comparison, the widely-used K band at 2.2 $\mu$m is greatly suppressed by strong CH$_4$ and H$_2$–H$_2$ absorption features. Beyond 13 $\mu$m, the decreasing flux falls slightly more rapidly than a Planck distribution with a brightness temperature near 600 K.

5. Potential for Direct Detection of EGPs

Imaging giant planets around nearby stars presents major technological challenges. The difficulties arise mainly from the following problems: 1) The brightness ratio between the star and the planet is large and ranges from $\sim 30$ to $10^3$, 2) The angular separation may range from 5" in the favorable case to a daunting 0.002", and 3) The flux from the planet is generally very low. These three factors stretch the current limits of optical and infrared technologies. Current and next-generation instruments are reaching sensitivity levels within the range of our predicted fluxes of EGP’s, but they do not always have sufficiently high angular resolution to resolve the EGP from its parent star. (The separations for the newly-discovered planets listed in Table 1 range from 0.002" for $\tau$ Boo B to 0.5" for 55 Cnc C.) The issue of angular resolution is further complicated by the problem of light scattered in the telescope optics. The point-spread function of diffraction-limited optical systems typically has a very faint halo which can spread over several arcseconds.
Figure 3. The grey shaded area shows the best-fit region for Gl229 B. Solid lines depict the evolution of $T_{\text{eff}}$ and $g$ as various mass brown dwarfs cool. The masses in Jupiter masses are indicated near the appropriate lines. Several contours of constant radius (long-dashed curves) and constant age (short-dashed curves) are also shown (from [10]).

around the Airy disk, due to minute residual errors in the figure of the mirror, light scattered inside the telescope, or residual atmospheric distortions of the images. Because of the enormous contrast between the planet and the primary star, the signal of the planet can be lost in the halo of the primary star. The brightness of this faint halo is very difficult to predict and is expected to vary widely from one instrument to another.

Detection of planets by direct techniques, i.e. imaging using adaptive optics or interferometric techniques, must also take into account the scattering of light by dust systems, analogous to our zodiacal light, around candidate stars. Further, such imaging in the mid-infrared is inhibited by our own zodiacal dust, requiring that infrared interferometers be placed in heliocentric orbits at 3 A.U. or beyond to avoid the worst of the dust emission (ExNPS report and R. Angel, personal communication).

Ignoring for the moment the question of angular resolution, Figure 4 compares the sensitivities of various ground-based and space-based telescopes with some theoretical fluxes calculated in [7] and [8] under the blackbody assumption. These comparisons help us gauge the capabilities of various platforms for giant planet searches and has led us to conclude that current technology will indeed be up to the challenge. Figure 4 depicts the flux in Jansky's versus wavelength at 10 parsecs for a 1 M$_J$ and a 5 M$_J$ EGP that are 5.2 A.U. from a G2 V star (a solar analog), at times between $10^7$ and $5 \times 10^9$ years. The reflected component is included in Figure 4. Also shown on Figure 4 are the $5\sigma$ point-source sensitivities at various wavelengths for the Space InfraRed Telescope Facility (SIRTF, [19]), the Large Binocular Telescope (LBT, [20]), the upgraded “Multiple Mirror” Telescope (MMT, [20]), Gemini [21], the Stratospheric Observatory For Infrared Astronomy (SOFIA, [22]), and NICMOS [23].

The three NICMOS (Near Infrared Camera and Multiple Object Spectrograph) cameras, with resolutions of 0.043, 0.075 and 0.2” respec-
Figure 4. Spectral dependence of the flux received at the Earth from extra-solar giant planets (EGPs) orbiting at 5.2 A.U. from a G2 V star at 10 parsecs from the Earth (The orbit subtends an angle of \( \sim 0.5'' \)), according to [7]. Objects of 1 M\(_J\) (solid curves) and 5 M\(_J\) (dashed curves) are displayed at the following ages: \( \log t(\text{yr}) = 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 9.7 \) (from left to right). The reflected component of the light is essentially independent of the mass and the age of the EGP. The EGP is assumed to emit like a blackbody and to reflect incident light as a grey body. Standard photometric bandpasses are shown at the top. Also shown are the design sensitivities of several astronomical systems for the detection of point sources with a signal-to-noise ratio of 5 in a 1-hour integration (40 minutes for NICMOS). These systems are the LBT and MMT (solid circles and square, respectively), the three cameras of NICMOS (open triangles, 3-pointed stars and solid triangles), SIRTF (solid bars), and Gemini and SOFIA (dashed bars). The spectrum of a G2 V star was provided by A. Eibl (private communication, 1995). It should be stressed that while SIRTF is unlikely to have the angular resolution to detect the EGPs of this example, the same EGPs at slightly larger separations around a star that is slightly closer will be well within its detection envelope.
tively, are very promising instruments for the detection of EGP’s in the solar neighborhood. They are sensitive in the near infrared where most EGP’s emit in reflected light. With the adaptive optics scheme proposed by Angel [20], both the MMT and the LBT will achieve diffraction-limited resolution ($\sim 0.025''$ and $\sim 0.014''$, respectively, at 0.8 $\mu$m) from the ground. Measurable star/planet flux ratios might be as high as $\sim 10^9$ for bright enough stars. Hence, the two telescopes will have sensitivities comparable to the NICMOS cameras at $\lambda = 0.8\mu$m and may successfully tackle the problem of scattered light. Gemini and SOFIA are sensitive at mid- to far-infrared wavelengths. This band spans the thermal emission of EGP’s, and the signal is predicted to be relatively insensitive to the type of central star. The sensitivity of SOFIA is too low to be useful at wavelengths beyond 10 $\mu$m. The lower angular resolution of these telescopes ($\sim 1''$ at best) limits useful searches to nearby systems with fairly large orbital radii.

SIRTF will have the highest angular resolution of all space-based instruments in the mid- to far-infrared. Its high sensitivity gives it a real chance of detecting the thermal emission of EGP’s in the solar neighborhood. SIRTF should be particularly good at searching for EGP’s around M dwarfs which are too faint in reflected light to be seen by other powerful instruments such as NICMOS and the LBT. Its expected angular resolution of $\sim 1 - 2''$ limits searches to favorable combinations of distance $D$ and orbital radius $a$. ISO (Infrared Space Observatory) was launched in 1995 and its 5 – 20 $\mu$m sensitivity is not much lower than that of SIRTF. The angular resolution of ISO is limited by its small aperture (0.6 m) and is further compromised by pointing jitter of 2.8$''$ (ISO Observer’s Manual [24]).

As is indicated in Figure 4, the LBT and NICMOS have the flux sensitivity to see at 10 parsecs the reflected light of such EGP’s at 5 A.U. at any age. At the diffraction limit, these instruments will also have the requisite angular resolution. At 10 parsecs, SIRTF has the flux sensitivity between 5 $\mu$m and 10 $\mu$m to detect the thermal emissions of both a 5 M$_J$ EGP, for ages less than $10^9$ years, and a Jupiter at 10 A.U., for ages less than $10^8$ years.

6. The Future

We have already preformed the first rudimentary calculations of the atmospheres, evolution, and spectra of extrasolar giant planets, in a variety of stellar environments. However, much remains to be done. Burrows et al. [7] and Saumon et al. [8] assumed that the time- and mass-dependent fluxes from EGP’s were Planckian. As our recent work on Gl229 B has shown, this assumption can be an order-of-magnitude off in the J, H, L’, and M bands. We are planning to construct an extended grid of non-grey boundary conditions and will soon perform evolutionary calculations, not only in the Gl229 B mass range (30 – 55 M$_J$), but in the EGP mass range from 0.3 M$_J$ to 15 M$_J$ (of relevance to the newly-discovered giant planets in Table 1). In this way, we will derive in a self-consistent fashion the spectra and colors of EGP’s as a function of mass and age. This expanded theory will provide a means of working back from a measured spectrum, $T_{\text{eff}}$, and gravity to the physical characteristics of the planet itself, assessible in no other way. Spectra and colors are worth little if they can’t be attached to masses, ages, and compositions. A complete and self-consistent theory of the evolution, emissions, and structure of extrasolar giant planets will be a crucial prerequisite for any credible direct search of nearby stars. The present pace of giant planet discovery and NASA’s and ESA’s [25] future plans for planet searches suggest that many more objects in the Jovian mass range (and above) will soon be identified and subject to spectroscopic examination.

REFERENCES

25. A. Leger, et al., Darwin Mission Concept,