Next-Generation Telescopes Can Detect Extra-Solar Giant Planets

A. Burrows*, D. Saumon†, T. Guillot‡†, W. B. Hubbard†, and J. I. Lunine†

*Departments of Physics and Astronomy, University of Arizona, Tucson, AZ 85721 USA
†Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721 USA
‡†Observatoire de la Côte d’Azur, CNRS/URA 1362, BP 229, 06304 Nice Cedex 4, France

Interest among astronomers in the detection of extra-solar planets is accelerating with the growing realization that it may soon be technically feasible. The ongoing renaissance in telescope construction and the anticipated launches of new space platforms are encouraging many scientists to review and improve the means by which planets can be discovered. The direct detection of the light from a distant planet would be the most compelling means of discovery and to gauge the feasibility of various search strategies, astronomers have traditionally used the current Jupiter as a benchmark planet. However, in principle, extra-solar giant planets (EGPs) can have a wide range of masses and ages, and, hence, can be significantly brighter than Jupiter. Furthermore, the maximum mass a planet can have is not known from first principles and observations will be needed to determine it. We predict the optical and infrared fluxes of EGPs with masses from 0.3 through 15 Jupiter masses and ages from $10^7$ through $5 \times 10^9$ years that searches in the next few years may reveal.

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. To calculate their cooling curves, we used the Henyey code previously constructed to study brown dwarfs and M dwarfs. Below effective temperatures ($T_{eff}$) of 600 K, we employed the atmospheres of Graboske et al., who included opacities due to water, methane, ammonia, and collision-induced absorption by H$_2$ and He. The gravity dependence of the EGP atmospheres was handled as in Hubbard. Above $T_{eff} = 600$ K, we used the X model of reference 15. The two prescriptions were interpolated in the overlap region. We employed the hydrogen/helium equation of state of Saumon & Chabrier and ignored rotation.
and the possible presence of an ice/rock core.\textsuperscript{20,21} The EGPs were assumed to be fully convective at all times. We included the effects of “insolation” by a central star of mass $M_\star$ and considered semi-major axes ($a$) between 2.5 A.U. and 20 A.U. Giant planets may form preferentially near 5 A.U.,\textsuperscript{22} but a range of $a$’s can not be excluded. We assumed that the Bond albedo of an EGP is that of Jupiter (0.35).\textsuperscript{23} For this study, we evolved EGPs with masses ($M_p$) from 0.3 $M_J$ (the mass of Saturn) through 15 $M_J$ ($M_J \cong 1.9 \times 10^{30}$ g, where $M_J$ is the mass of Jupiter). 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. Note that any search for giant planets will perforce be even more capable at discovering brown dwarfs.

The evolution of the bolometric luminosity ($L_{bol}$) of our suite of EGPs orbiting 5.2 A.U. from a G2 V star 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,\textsuperscript{16,17,20,21,24,25,26} 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 the current Jupiter (and its $T_{eff}$ 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 $T_{eff} \sim 420$ K) and at the age of the Hyades ($\sim 6 \times 10^8$ years) it would be $\sim 18$ times brighter (with $T_{eff} \sim 235$ K). The measured $L_{bol}$ and $T_{eff}$ of Jupiter are $2.186 \pm 0.022 \times 10^{-9} \ L_\odot$ and $124.4 \pm 0.3 \ K$, respectively.\textsuperscript{27} 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 complete discussion of our results is deferred to a later paper (Saumon \textit{et al.}, in preparation). However, a few “facts” will serve to illustrate the character of massive, young
EGPs. Since the fluxes shortward of 10 µm (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 $L_{bol}$. In particular, assuming that the emission is Planckian, that the orbital separation is 5.2 A.U., and that $M_*$ 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 $2 M_J$ EGP and a $5 M_J$ EGP would be $\sim 6$ and $\sim 90$ times brighter in the N band than the current Jupiter. Furthermore, in the M band ($\sim 5$ µm), a $2 M_J$ 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 at Earth due to the thermal emissions shortward of 10 µm 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 $T_{eff}$).

In this paper, we focus on the crucial question of the brightness of EGPs as a function of age and mass to aid in the development of search strategies. However, the detection of EGPs requires telescopes with both high sensitivity and high angular resolution. The latter is necessary to discriminate the planet from the star and can be compromised by the presence of scattered light in the telescope optics. Nevertheless, it is expected that the Large Binocular Telescope$^2$ (LBT), the Near Infrared Camera and Multi-Object Spectrometer$^4$ (NICMOS), and the Space InfraRed Telescope Facility$^5$ (SIRTF) will have both the sensitivity and the angular resolution (see caption for Figure 3) to discover EGPs with a variety of realistic combinations of $a$ and $D$. It is not our purpose here to discuss various detection strategies, nor to explore the consequences of every combination of $M_p$, $M_*$, $a$, $D$, and telescope. Rather, in Figures 2 and 3, we compare theoretically predicted fluxes for a few representative values of $a$ and $D$ and various EGP ages and masses with the flux sensitivities of various ground- and space-based telescopes currently being developed.

Figure 2 depicts the flux in Janskys 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. We have made the assumption that the thermal emissions are blackbody and have included the reflected light. Also shown on Figure 2 are the $5\sigma$ point-source sensitivities at various wavelengths for SIRTF,$^4$ the LBT,$^2$ the upgraded “Multiple Mirror” Telescope$^2$ (MMT), Gemini,$^3$ the Stratospheric Observatory For Infrared Astronomy$^{28}$ (SOFIA), and the three NICMOS cameras.$^4$ As is indicated in Figure 2, the LBT and NICMOS have the flux sensitivity to see at 10 parsecs the reflected light of such EGPs 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. Figure 3 shows the fluxes from EGPs with masses between $0.3 M_J$ and $5 M_J$ orbiting at 10 A.U. around an A0 V star (e.g., a Vega analog) at a distance of 10 parsecs from the Earth. Its age is $2 \times 10^8$ years, just shy of its main-sequence lifetime. It can be seen that the reflected light from all EGPs at 10 A.U. around such a bright star will be detectable by the LBT, the MMT, and NICMOS, since all these platforms will achieve angular resolutions well below $1''$. Furthermore, the SIRTF sensitivities in the mid-IR would be just adequate to see even a Saturn-mass object around an A0 V star at this age, distance, and separation. Though SIRTF may not achieve the necessary $1''$ performance, it should have the angular resolution to discover similar EGPs at somewhat smaller $D$’s and larger $a$’s.

Interestingly, NICMOS is sensitive enough to detect any widely-separated EGP with a mass greater than $6 M_J$ around any main-sequence star as far away as the Pleiades, while SIRTF has the sensitivity to detect any “free-floating EGPs” in the Pleiades with a mass greater than $4 M_J$. This is because the internal energy of a young EGP alone is adequate to power it in the relevant spectral bands. None of the anticipated telescope systems will have the angular resolution to probe for an EGP in the Pleiades, unless it is many tens of A.U. from its central star.
Clearly, searches around early main sequence stars or in very young stellar systems will select for the youngest and most massive planets. Crude models of giant planet formation around a solar-mass star permit objects up to 10 Jupiter masses to form.\textsuperscript{12} The most massive planet in our solar system is Jupiter and why there are none more massive is not understood. The lifetime of our gaseous proto-planetary disk may have been short\textsuperscript{29} or the disk may have been tidally truncated by the growing planet itself.\textsuperscript{13} Good statistics on the population of EGPs will better constrain proto-planetary disk processes. The absence of a Jupiter-class planet in a planetary system would imply a very different population of cometary-sized planetesimals than exists in our own solar system, and this may have important implications for the origin, evolution, and survival of life on rocky “terrestrial” planets.\textsuperscript{30} Only sensitive and systematic searches such as those we anticipate over the next decade will directly address these important issues of planet formation.
References

1. TOPS: Toward Other Planetary Systems (NASA Solar System Exploration Division, Washington, D.C. 1992).
2. Angel, R. *Nature* **368**, 203-207 (1994) (LBT and MMT).
3. Mountain, M., R. Kurz, R., & Oschmann, J. in *The Gemini 8-m Telescope Projects*, *S.P.I.E. Proceedings on Advanced Technology Optical Telescopes V* **2199**, p. 41 (1994).
4. Thompson, R. *Space Science Reviews* **61**, 69-63 (1992) (NICMOS).
5. Erickson, E. F. & Werner, M. W. *Space Science Reviews* **61**, 95-98 (1992) (SIRTF).
6. Benvenuti, P. *et al.* in *ESA’s Report to the 30th COSPAR Meeting, ESA SP-1169, Paris*, p. 75 (1994) (ISO).
7. Gatewood, G. D. *Astron. J.* **94**, 213 (1987).
8. Reasenberg, R. D. *et al.* *Astron. J.* **96**, 1731 (1988).
9. Walker, G.A.H. *et al.* *Icarus*, in press (1995).
10. Mao, S. & Paczynski, B. *Astrophys. J.* **374**, L37 (1991).
11. Borucki, W. J. & Summers, A. L. *Icarus* **58**, 121 (1984).
12. Podolak, M., Hubbard, W. B., & Pollack, J. B. in *Protostars and Planets III*, eds. E. Levy & J. I. Lunine, University of Arizona Press, P. 1109 (1993).
13. Lin, D.N.C. & Papaloizou, J. *M.N.R.A.S.* **186**, 799 (1979).
14. Burrows, A., Hubbard, W. B., & Lunine, J. I. *Astrophys. J.* **345**, 939 (1989).
15. Burrows, A., Hubbard, W. B., Saumon, D., & Lunine, J. I. *Astrophys. J.* **406**, 158 (1993).
16. Graboske, H. C., Pollack, J. B., Grossman, A. S., & Olness, R. J. *Astrophys. J.* **199**, 265-281 (1975).
17. Hubbard, W. B. *Icarus* **30**, 305 (1977).
18. Saumon, D. & Chabrier, G. *Phys. Rev. A* **44**, 5122-5141 (1991).
19. Saumon, D. & Chabrier, G. *Phys. Rev. A* **46**, 2084-2100 (1992).
20. Pollack, J. B. *Ann. Rev. Astron. Astrophys.* **22**, 389 (1984).

21. Bodenheimer, P. & Pollack, J. B. *Icarus* **67**, 391 (1986).

22. Boss, A. P. *Science* **267**, 360 (1995).

23. Conrath, R. A., Hanel, R. A., & Samuelson, R. E. in *Origin and Evolution of Planetary and Satellite Atmospheres*, University of Arizona Press, p. 513 (1989).

24. Saumon, D., Hubbard, W. H., Chabrier, G., & Lunine, J. I. *Astrophys. J.* **391**, 827 (1992).

25. Guillot, T., Chabrier, G., Gautier, D., & Morel, P. *Astrophys. J.*, in press (1995).

26. Black, D. C. *Icarus* **43**, 293-301 (1980)

27. Pearl, J. C. & Conrath, R. A. *J. Geophys. Res. Suppl.* **96**, 18921-18930 (1991).

28. Erickson, E. F. *Space Science Reviews* **61**, 61-68 (1992) (SOFIA).

29. Zuckermann, B., Forveille, T., & Kastner, J. H. *Nature* **373**, 494-496 (1995).

30. Wetherill, G. W. *Lunar Planet. Sci. Conf. XXIV*, 1511 (1993).

31. Dreiling, L. A. & Bell, R. A. *Astrophys. J.* **241**, 736-758 (1980)

Acknowledgment: The authors would like to thank Roger Angel, Nick Woolf, George Rieke, Frank Low, Peter Eisenhardt, Dave Sandler, and Glenn Schneider for many fruitful discussions on detector technology and for providing us with instrument specifications and NASA, the US NSF, the Hubble Fellowship Program, and the European Space Agency for financial support.
FIGURE CAPTIONS

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.\(^{27}\) 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.

Figure 2: 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 $\sim 0.5''$). Objects of 1 $M_J$ (top panel) and 5 $M_J$ (bottom panel) 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 (see caption for Figure 3).
Figure 3: Same as Figure 2, but for EGPs orbiting 10 A.U. from an A0 V star whose age is
$2.0 \times 10^8$ years and whose distance is 10 parsecs. (The angular separation is 1$''$.) From
left to right, the curves correspond to masses of 5, 4, 3, 2, 1, 0.5 and 0.3 $M_J$. The
spectrum of an A0 V star is from Dreiling & Bell. Note that the heating by this star at
10 A.U. is quite significant for all lower-mass EGPs and that the reflected component
of an EGP is $\sim 80$ times brighter when it orbits an A0 V star than when it orbits a
G2 V star. The MMT, the LBT, and NICMOS (on the Hubble Space Telescope), with
apertures of 6.5 meters, 8.4 meters ($\times 2$), and 2.4 meters, respectively, will achieve
angular resolutions near their respective diffraction limits (R. Angel, N. Woolf, and
G. Schneider, private communications). Being a mid-infrared platform with a 0.85-
meter aperture, SIRTF’s angular resolution will, quite naturally, be poorer than that
of the optical and near-infrared platforms. However, with super-resolution techniques,
SIRTF should be able to resolve EGPs at somewhat larger $a$’s and smaller distances
than used for this figure (F. Low, private communication).
1 M$_f$ EGP
G2 V primary
$a = 5.2$ AU

5 M$_f$ EGP
G2 V primary
$a = 5.2$ AU
