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Exoplanet Atmospheres and Giant Ground-Based Telescopes

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The study of extrasolar planets has rapidly expanded to encompass the search for new planets, measurements of sizes and masses, models of planetary interiors, planetary demographics and occurrence frequencies, the characterization of planetary orbits and dynamics, and studies of these worlds' complex atmospheres. Our insights into exoplanets dramatically advance whenever improved tools and techniques become available, and surely the largest tools now being planned are the optical/infrared Extremely Large Telescopes. Two themes summarize the advantages of atmospheric studies with the ELTs: **high angular resolution** when operating at the diffraction limit and **high spectral resolution** enabled by the unprecedented collecting area of these large telescopes. This brief review describes new opportunities afforded by the ELTs to study the composition, structure, dynamics, and evolution of these planets' atmospheres, while specifically focusing on some of the most compelling atmospheric science cases for four qualitatively different planet populations: highly irradiated gas giants, young, hot giant planets, old, cold gas giants, and small planets and Earth analogs.

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[*] Speaker.
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1. Introduction and Overview

Over the past two decades, the study of extrasolar planets has grown more rapidly than any other field of astronomy. Once the province of only a small number of explorers, hundreds of researchers across our globe now work to find new planets, measure their sizes and masses, model planetary interiors, measure the intrinsic frequency with which planets occur, characterize planetary orbits and dynamical interactions, and observe and model the complex atmospheres of these other worlds.

Our insights into exoplanets dramatically advance whenever improved instruments, facilities, and/or observing techniques become available. Surely the largest astronomical assets now being planned are the so-called Extremely Large Telescopes (ELTs) – the next generation of large-aperture, optical/infrared-optimized, ground-based telescopes. These include the 25 m-diameter GMT [1], 30 m TMT [2], and the 39 m E-ELT [3]. Though none of these projects are fully funded as of this writing, it seems likely that at least one ELT (and hopefully more) will see first light in the mid-2020s.

The ELTs and their instruments will revolutionize all areas of exoplanet science — not to mention most other sub-fields of astronomy. Two themes summarize the advantages of atmospheric studies with the ELTs: **high angular resolution** when operating at the diffraction limit and **high spectral resolution** enabled by the unprecedented collecting area of these large telescopes. When using adaptive optics (AO) to operate at the diffraction limit, angular resolution scales inversely with telescope diameter as λ/D and so with sensitivity increases as D^4 during AO operations. Even during seeing-limited observations (when sensitivity scales as D^2) an ELT's larger aperture makes high-resolution spectroscopy feasible on a much wider array of targets.

This brief review focuses on one particular aspect of exoplanet science: measurement of the composition, structure, dynamics, and evolution of these planets' atmospheres. In a sense, this work complements the recently-published broad overview of exoplanet atmospheres [4] by focusing specifically on the potential benefits that these the ELTs' high-resolution advantages will bring to future studies in this field. This work specifically focuses on some of the most compelling atmospheric science cases for four qualitatively different planet populations: highly irradiated gas giants (Sec. 3), young, hot giant planets (Sec. 4), old, cold gas giants (Sec. 5), and small planets and Earth analogs (Sec. 6).

2. Instruments and Techniques

The main obstacle preventing detailed atmospheric characterization beyond the Solar System is the challenge of obtaining high-precision measurements of an exoplanet mostly obscured by the glare of its bright host star. For example, a "hot Neptune" and a cool T-type brown dwarf may have comparable luminosities: yet while dozens of the latter are routinely studied by today's ground-based telescopes [5], only a handful of the former have been studied even after many hours of dedicated space telescope spectroscopy [6, 7].

Atmospheric observations seek to somehow disentangle the fainter planetary signature from the much brighter stellar signal. This goal is achieved in different ways for different types of planets, typically involving high angular and/or spectral resolution. Table 1 summarizes the ba-

Table 1. ELT Instruments for Exoplanet Exploration

Description	E-ELT	TMT	GMT
$R \sim 10^5$, MIR, slit/IFU	**METIS**	MICHI	GMTNIRS
$R \sim 10^5$, NIR, slit	HIRES	NIRES	
$R \sim 10^5$, optical, fiber		HROS	**G-CLEF**
$R \sim 3000$, NIR, IFU	**HARMONI**	**IRIS**	GMTIFS
High-contrast imager/IFU	EPICS	PFI/PSI	TIGER

Instruments in **bold** are planned for first light operations.

sic properties of some representative ELT instruments that might be most useful for atmospheric characterization, along with each project's current name for such an instrument.

For planets on shorter-period orbits ($P \lesssim 20$ d), the coherent Doppler shift of the planet's intrinsic emission (and perhaps also reflection) spectrum can help separate the planet from the star. The planet-star system effectively becomes a spectroscopic binary! Hence the benefit of **high spectral resolution**, which more effectively resolves the high-resolution planetary lines (a tidally-locked hot Jupiter with Jupiter's radius and $P = 1$ d has $v \sin i = 5$ km s^{-1}). High-resolution transit spectroscopy does not necessarily rely on a high planetary velocity, but increased spectral resolution still helps to separate the qualitatively different planetary and stellar spectra. Planets on longer-period orbits experience much lower accelerations and so Doppler-shift analyses are less effective (though, as during transits, high spectral resolution can provide key benefits in certain cases). More commonly, such a planet is distinguished as a separate point source near its host star thanks to **high angular resolution** imaging, and diffraction-limited instruments specially designed to suppress the star's bright, scattered-light halo. When coupled to medium- or high-resolution spectrographs, such instruments become even more powerful.

3. Irradiated Gas Giants

Most exoplanet atmospheres studied to date are those of highly irradiated gas or ice giants: mostly hot Jupiters (known now for over two decades; [12, 13]) with small but growing numbers of hot Neptunes and mini-Neptunes [14, 15, 16]. These planets share a few common characteristics: all are large enough that they must contain substantial mass fractions of volatiles (H_2/He, H_2O, etc.), and all have short orbital periods ($P < 10$ d) that subject the planets to much higher levels of irradiation than seen in the Solar System.

Models of these exotic atmospheres suggest many fascinating phenomena that may be amenable to observation. As described elsewhere [4], these phenomena include day-to-night temperature contrasts of hundreds to thousands of K [17], circumplanetary wind speeds of up to several km s^{-1} that redistributes this incident heat [17], atmospheric composition that reflects the planet's formation and migration history [18, 19], unusual atmospheric abundance patterns and metallicity enhancements 1000× or more above the Solar composition [20, 21, 22], temperature inversions in the low to upper atmosphere [23, 24], and spatially varying abundances and thermal structure [25, 26].

These short-period planets are best characterized via **high spectral resolution** observations, since they orbit too near their host stars to be resolved separately (0.1 AU/10 pc = 10 mas, or $\sim 1\lambda/D$ for an ELT). Indeed, the first atmospheric characterization of any exoplanet's atmosphere was the detection of Na in the hot Jupiter HD 209458b via high-resolution optical spectroscopy during transit [27]. Subsequent observations have revealed Na and/or K in the atmospheres of a growing number of hot Jupiters (see [28] for a recent summary). When observed at high S/N and high spectral resolution, such observations probe alkali abundances and the thermal structure of a planet's atmosphere [29, 30], as well as measuring the wind speeds on both the dawn and twilight terminators [31, 32]. After many years of searching, the first ground-based measurement of an exoplanet's albedo has also recently been made using high-resolution optical spectroscopy [33]. ELT instruments will measure all these quantities for a much wider range of planets than the few studied in this way to date, and will provide much higher-precision measurements of these phenomena for the most observationally favorable systems.

Spectroscopy in the infrared is an even more powerful diagnostic of short-period exoplanet atmospheres than are optical observations. The planet/star contrast ratio is more favorable at longer wavelengths and because these wavelengths host many more (and stronger) molecular lines than do shorter wavelengths. As a result, this technique has rapidly progressed from mere detection of molecules [34] and constraints on cloud properties [35] to high-precision measurements of atmospheric abundances of CO, H_2O, CH_4, and C/O ratios; orbital inclinations (and so absolute masses) of non-transiting planets; thermal structure; and global rotation and winds (Fig. 1b; [36, 8, 37, 38, 39, 40, 41, 42, 43]).

ELT high-resolution infrared spectroscopy will push these studies to larger numbers of smaller, cooler planets (to date, nearly all such studies have focused on hot Jupiters). The one exception was a non-detection consistent with GJ 1214b's cloud-covered atmosphere [35, 6]. Fortunately

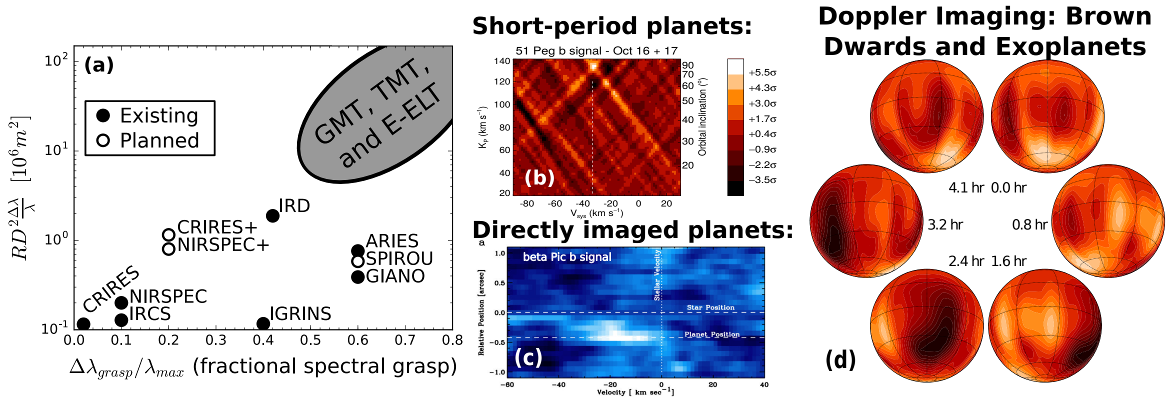

Figure 1 The promise of high-dispersion spectroscopy: *(a):* New and increasingly powerful infrared spectrographs offering broad spectral grasp and high spectral resolution enable transformative atmospheric characterization. These will be ideal for *(b)* measurements of atmospheric abundances, thermal structure, and atmospheric dynamics of short-period exoplanets [8]; *(c)* measurements of 3D orbits, angular momentum and rotation, and atmospheric compositions of directly imaged planets [9]; and *(d)* Doppler Imaging of brown dwarfs and exoplanets to create 2D global maps and weather movies, tracking atmospheric makeup, cloud formation and dissipation, and global circulation [10, 11].

some sub-Jovian, sub-1000 K planets have at least partially cloud-free atmospheres [44] and so new types of planets will certainly be amenable to high-resolution spectroscopy. Furthermore, the impact of clouds is greatly reduced when studying a planet's thermal emission (rather than transmission) spectrum [45], providing an alternative avenue for study. With broader wavelength coverage and greater collecting area than existing instruments, the improved capabilities of these new instruments (see Fig. 1a) will allow future studies to measure precise atmospheric abundances, measure global wind patterns and energy recirculation [46, 47, 48], and (by observing at multiple orbital phases) create longitudinally-averaged global maps of composition, clouds, and thermal structure (e.g., [49]).

4. Young, Hot Giant Planets

The process of planet formation is a violent and, above all, energetic process. After accretion of rocky solids into planetary cores, considerable energy is liberated during the runaway accretion experienced by gas giants; models of planet formation predict that for a young, giant protoplanet achieves a luminosity as great as $\sim 10^{-4} L_{\odot}$ [50] for a few Myr. During this time the system exhibits an exceedingly favorable planet/star contrast ratio. Furthermore, if gas accretion is ongoing then traditional stellar activity indicators (e.g., Hα emission) may be detectable as well. Indeed, young accreting planets have been imaged around a few nearby systems [51, 52, 53, 54]. However, such targets are near the limit of what can be studied using current facilities – with a main limitation being the < 0.1” separations of these objects from their host stars. The **high angular resolution** of a diffraction-limited ELT is essential to to study a large, representative sample of these young, accreting objects. For example, the study of young, giant protoplanets during formation was one of the key science drivers behind the original instrument concept study for the TMT's Planet Formation Instrument [55].

Although giant planets at later ages (up to 100 Myr) are somewhat fainter, observations (mostly photometry) have revealed considerably more about their atmospheric composition, non-equilibrium chemistry, luminosity & thermal evolution, and even bulk angular momentum [56, 57, 9, 58, 59, 60]. All these studies would benefit from the **high angular resolution** and increased sensitivity that an ELT's larger apertures would provide, and many more such systems should be discovered by GAIA and ongoing ground-based surveys by the time the ELTs begin operations. Recent observations reveal the even greater power of medium- to high-resolution spectroscopy (as opposed to photometry) when determining these planets' atmospheric properties [56, 9, 58]. Instruments that combine both high spatial resolution and medium-to-high spectral resolution may therefore provide especially exciting opportunities to expand the range of planets accessible to studies of composition, chemistry, and clouds. Such instruments also raise the possibility of photometric and/or spectroscopic monitoring of intrinsic variability (weather) on these objects (e.g., [61]).

The ELTs will also provide exciting opportunities to produce global, two-dimensional maps via Doppler Imaging. Fig. 1d shows the first 2D map of a brown dwarf produced using this technique [10]. ELT-based high-resolution infrared spectrographs should have the sensitivity to conduct such observations for at least a small number of the brightest directly imaged exoplanets [9, 11]. These studies will produce global Doppler maps and weather movies of exoplanets (and many brown dwarfs). By tracking the atmospheric dynamics and the formation, evolution, and dissipa-

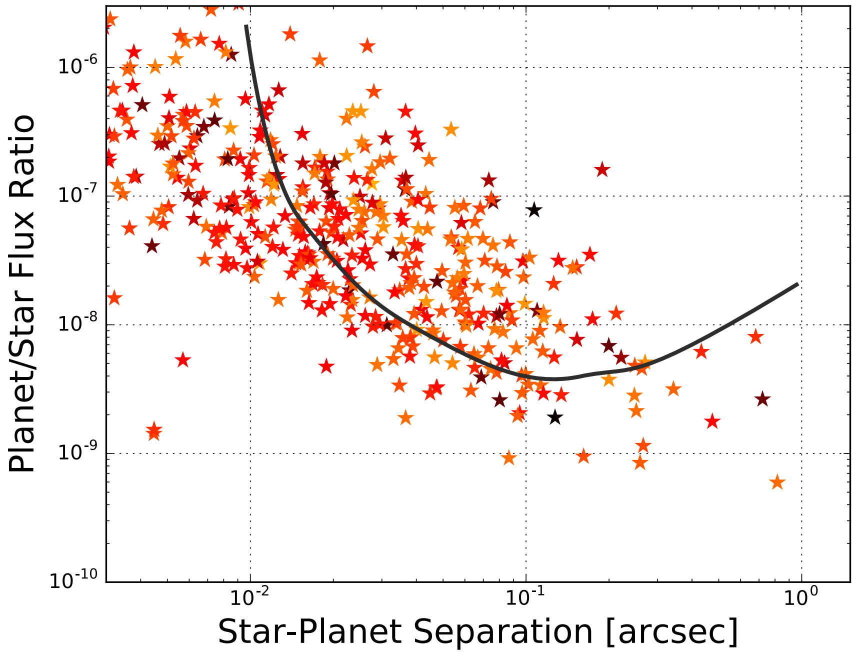

Figure 2 Known RV planets potentially accessible to NIR high-contrast observations in reflected light. Data are taken from the NASA Exoplanet Archive. The only assumptions are an albedo of 0.1, $R_p/R_\oplus = (M_p/M_\oplus)^{0.485}$, and the radii of all planets with $R_P/R_J > 1.8$ and $M_p/M_J > 1.8$ set to $1.2R_J$. The solid line is the approximate contrast performance predicted for ELT instruments, and the color scale indicates $T_{\rm eff}$. The accessible systems are mostly Jovian-size planets orbiting beyond 1 AU.

tion of clouds in these atmospheres, Doppler imaging could provide exciting and unique insights into the atmospheric properties of these bodies.

5. Mature, Cold Gas Giants

Most high-contrast, direct imaging instruments operate in the near-infrared and are sensitive only to the young, hot, self-luminous giant planets on wide orbits described above. The increased performance (in both sensitivity and achievable planet/star contrast) of ELT-based high-contrast instruments should allow the detection of many old, cold, mature giants in reflected starlight around nearby stars [62]. The large numbers of ice-line gas giants detected by radial velocity surveys [63, 64] indicate that there should be substantial numbers of giant planets accessible to high-contrast characterization in *reflected* light, as shown in Fig. 2. For the first time, these observations will allow the detailed comparison of significant numbers of albedos, cloud and haze properties, and atmospheric abundances and chemistry of gas giants only marginally warmer than Jupiter and Saturn. Such studies will directly complement characterization of smaller numbers of somewhat cooler giants with the WFIRST/AFTA coronagraph [65, 66, 67].

6. Small Planets and Earth Analogs

Cooler, smaller, and more nearly Earth-like planets will remain inaccessible to WFIRST/AFTA. Yet atmospheric characterization of small, rocky planets lies within reach of the ELTs through **high angular and/or spectral resolution**. When orbiting the nearest stars to the Sun, such planets will be accessible via high-contrast imaging observations. Using the measured occurrence rates of small planets around main-sequence stars measured by Kepler [68], Monte Carlo simulations show that 10–20 short-period, sub-Jovian planets should be detectable with future ELT instruments [69]. A few of the known, potentially accessible systems plotted in Fig. 2 are already smaller than Neptune, so a preliminary target list already exists. A fraction of these small, short-period planets could be observed in both reflected light ($< 2.5\,\mu$m) and thermal emission ($\sim$3–10 μm), with the former measuring albedos and cloud properties and the latter measuring radiometric radii for these planets [69]. Radial velocities will measure planet masses, and will also predict the most favorable times to observe these systems (i.e., at quadrature).

One of the most exciting and challenging long-term goals of exoplanet studies is the atmospheric characterization of Earth analogs: temperate, rocky planets with secondary atmospheres. The high-contrast instruments described above should be able to detect such planets orbiting early-to-mid M dwarfs within 20 pc, as shown in Fig. 3. Earth analogs orbiting earlier-type stars are too faint relative to their host star; those around later-type stars orbit too close to be resolved for all but the nearest systems. Based on predicted instrument performance, Fig. 3 shows that roughly 50 such systems could be detected if every star hosted such a planet. Since only one in six M dwarfs hosts a rocky planet in its Habitable Zone [70], we should expect 5–10 temperate, rocky planets within reach of ELT **high angular resolution** instruments.

Alternatively, the atmospheres of small, rocky planets may be studied in transit using the same **high spectral resolution** techniques currently applied to hot Jupiters. The application of this approach to seeking potential biosignature gases (e.g., O_2) has been studied many times over the past two decades [71, 72, 73, 74]. The latest (and most complete) treatment of such observations indicates that if all visible transits are observed over a long period, one could build up the S/N necessary for a confident detection. The timescale involved would be of order 10 years, but only of order 45 transits would be optimally observable and so the required observing time would be quite manageable ($\sim$10 hr/yr). Though applied here to O_2, the same approach could also likely characterize the abundances of other species such as CO_2, CH_4, H_2O, etc. on small planets of all types and temperatures.

Finally, small and temperate exoplanets may also be studied using a combination of both **high spectral and high angular resolution**. This approach may be best-suited for integral field spectrographs, though if a planet's location is well-known then AO-fed, slit-based spectrographs may also suffice. The success of both types of instruments when applied to known directly imaged planets [56, 9, 58] indicates the promise of this technique, and several studies have already considered the applicability of this approach — again, in the specific context of seeking potential biosignature gases [75, 76].

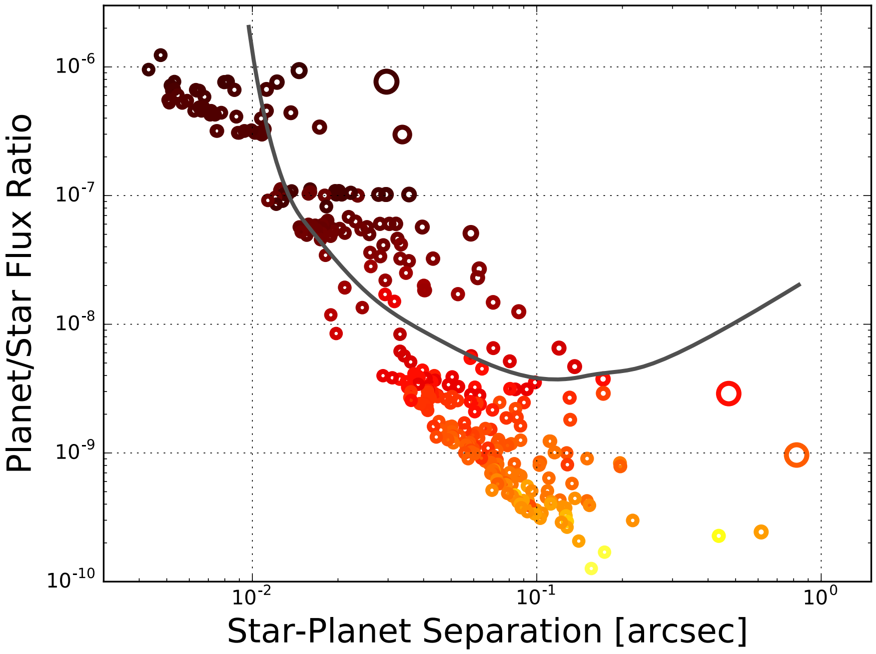

Figure 3 Accessibility of hypothetical temperate, rocky planets to NIR high-contrast observations in reflected light. Each point represents a 1.25 $R_\oplus$ planet receiving Earth-like irradiation, with one such planet for each star within 20 pc. The solid line is the approximate contrast performance predicted for ELT instruments. The color scale indicates $T_{\rm eff}$, and point size scales inversely with distance from Earth. The most accessible temperate planets will orbit M1–M4 dwarfs.

7. Conclusions

The approaching era of extremely large ground-based telescopes will be an exciting time for exoplanet science, and for atmospheric studies in particular. In the intervening years great strides will be made with JWST at low and medium spectral resolution, and at wavelengths from $< 1\,\mu$m to $\geq 12\,\mu$m. The key advantage of the ELTs will be their ability to deliver both **high spectral resolution** and **high angular resolution** far beyond what JWST will offer.

High-resolution spectrographs offer exciting opportunities for measuring the composition, dynamics, structure, and cloud properties of exoplanetary atmospheres. Fig. 1 shows the science cases soon to be enabled: global Doppler mapping of a few exoplanets and many brown dwarfs; atmospheric composition, dynamics, and thermal structure of short-period gas giants and sub-Jovians; rotation measurements of directly imaged planets; and more.

High-resolution imaging and/or IFU spectroscopy will complement the above studies by studying the composition, albedo, and cloud properties of old, cold gas giants inaccessible to current atmospheric characterization (see Fig. 2). Similar techniques should even permit the atmospheric study of smaller numbers of rocky planets — and (as shown in Fig. 3) perhaps even temperate, Earth-sized planets orbiting nearby M dwarfs.

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