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Exoplanet atmospheres: A theoretical outlook

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Abstract. With over two dozen exoplanet atmospheres observed today, the field of exoplanet atmospheres is solidly established. The highlights of exoplanet atmosphere studies include: detection of molecular spectral features; constraints on atmospheric vertical temperature structure; detection of day-night temperature gradients; and a new numerical approach to atmosphere temperature and abundance retrieval. As hot Jupiter observations and interpretation are maturing, the next frontier is super Earth atmospheres. Theoretical models of super Earth atmospheres are moving forward with observational hopes pinned on the *James Webb Space Telescope*, scheduled for launch in 2014. Further in the future lies direct imaging attempts to answer the enigmatic and ancient question, "Are we alone?" via atmospheric biosignatures.

Keywords. astrobiology, planetary systems, techniques: photometric

1. Introduction

At the dawn of the first discovery of exoplanets orbiting sun-like stars in the mid-1990s, few believed that observations of exoplanet atmospheres would ever be possible. After the 2002 Hubble Space Telescope detection of a transiting exoplanet atmosphere, many skeptics discounted it as a one-object, one-method success. By 2010, the field was firmly established, with over two dozen exoplanet atmospheres observed today. Hot Jupiters. the type of exoplanet most amenable to study are observed by the dozens. Highlights include, detection of molecular spectral features; observation of day-night temperature gradients; and constraints on vertical atmospheric structure. Atmospheres of giant planets far from their host stars are also being studied with direct imaging. The ultimate exoplanet goal is to answer the enigmatic and ancient question, "Are we alone?" via detection of atmospheric biosignatures. The two paths forward are the near-term focus on transiting super Earths orbiting in the habitable zone of M-dwarfs, and ultimately the space-based direct imaging of true Earth analogs.

2. Past: A Brief History of Exoplanet Atmospheres

The dawn of the discovery of exoplanets orbiting sun-like stars took place in the mid 1990s, with the birth of radial velocity detections. Because of selection effects, many of the exoplanets found in the first few years of discovery orbited extremely close to their host star. Called hot Jupiters, these planets orbit many times closer to their star than Mercury does to our sun. With semi-major axes 0.05 AU, the hot Jupiters are heated externally by their stars to temperatures of 1000-2000 K, or even higher. From the start the high temperature and close stellar proximity of hot Jupiters were recognized as favorable for atmospheric detection (Seager & Sasselov 1998). Even as the number of exoplanet

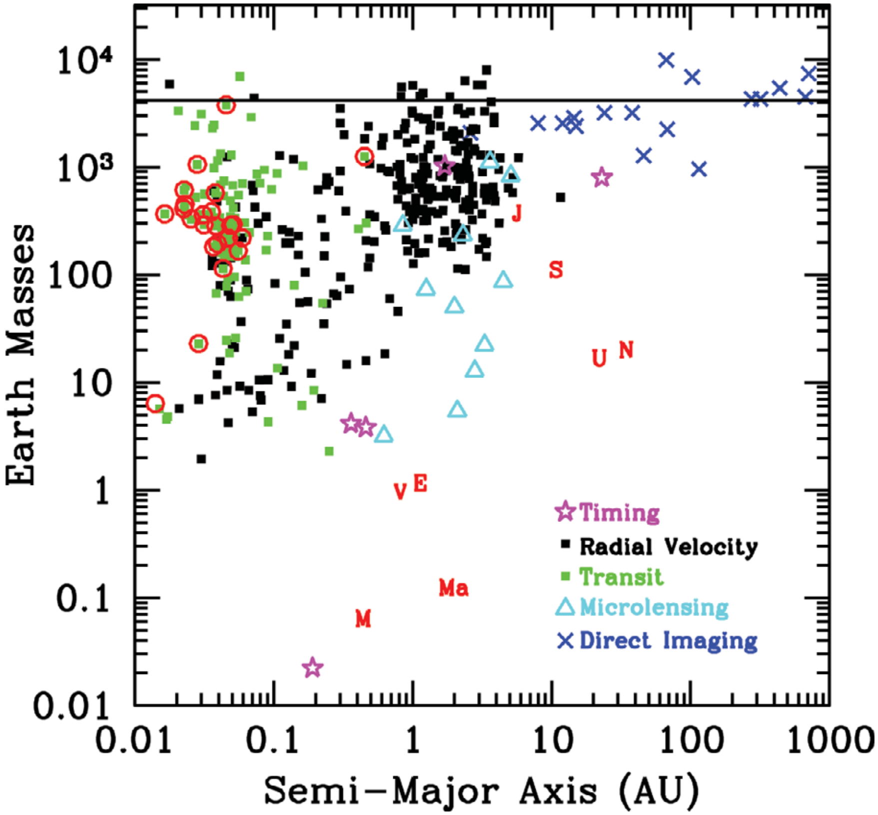

Figure 1. Known planets as of March 2010. Red letters indicate solar system planets. The red circles represent planets with published atmosphere detections. The solid line is the conventional upper mass limit for the definition of a planet. Data taken from http://exoplanet.eu/

detections grew in the late 1990s (just under 30 by the end of the 20th century†), few thought that exoplanet atmospheres could be observed at any time in the foreseeable future.

By the time about seven hot Jupiters were known, the community expected one to transit. With a probability to transit of $R_\star/a$, where $R_\star$ is the stellar radius and a is the semi-major axis, each hot Jupiter has about a 10% chance to transit. Seager & Sasselov (2000) presented transit transmission spectra as a way to detect the atmospheres of hot Jupiters, by way of atomic and molecular transmission spectral features, with a focus on sodium. HD 209458b was found to show transits at the end of 1999 (Charbonneau *et al.* 2000; Henry *et al.* 2000), and the first detection of an exoplanet atmosphere, via atomic sodium, with the Hubble Space Telescope soon followed (Charbonneau *et al.* 2002).

The theory of exoplanet atmospheres was also developing in the 1990s and early 2000s. At that time, theory was leading observation, and observers consulted the model predictions to help define the most promising detection techniques. Most theory papers focused on irradiated hot Jupiters, emphasizing spectral features and 1D temperature/pressure profiles resulting from the intense heating by the host star (Seager & Sasselov 1998; Marley *et al.* 1999; Sudarsky, Burrows, & Pinto 2000; Barman, Hauschildt & Allard 2001. Cloud modeling (Ackerman & Marley 2001; Cooper *et al.* 2003) and atmospheric

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† http://exoplanet.eu/catalog.php

circulation (Showman & Guillot 2002; Cho *et al.* 2003) were also expected to be important. Calculation of exoplanet illumination phase curves, polarization curves (Seager, Whitney, & Sasselov 2000), and especially transmission spectra (Seager & Sasselov 2000; Brown 2001; Hubbard *et al.* 2001) set the stage for observed spectroscopy during transit.

The Spitzer Space Telescope, launched in August 2003 revolutionized exoplanet atmosphere observations and hence theoretical modeling for interpretation. At mid-infrared wavelengths, hot Jupiters have a high planet-to-star contrast ratio, and the star and planet typically are bright enough to allow high precision photon-limited measurements. A flood of secondary eclipse observational detections came from Spitzer since 2005. Now hundreds of exoplanets are known (Figure 1). Dozens of hot Jupiters have been observed, creating the field of exoplanet atmospheres.

Here we summarize exoplanet atmosphere highlights then enumerate future prospects. For a full review, see Seager & Deming (2010).

3. Present: Recent Highlights

Hot Jupiters dominate recent exoplanet atmosphere science, because their large radii, extended atmospheric scale heights, and high temperetures make atmosphere measurements possible.

3.1. *Hot Jupiters are Hot and Dark*

Hot Jupiters are blasted with radiation from the host star and thus should be kinetically hot. The first and most basic conclusion from the Spitzer secondary eclipse detections was the confirmation of this basic paradigm. The fact that the planets emit generously in the infrared implies that they efficiently absorb visible light from their stars. Searches for the reflected component of their energy budget have indicated that the planets must be very dark in visible light, with geometric albedos less than about 0.2 (Rowe *et al.* 2008), and likely much lower. Models show that purely gaseous atmospheres lacking reflective clouds will be very dark (Marley *et al.* 1999; Seager, Whitney, & Sasselov 2000).

3.2. *Identification of Atoms and Molecules*

A major achievement for exoplanet atmospheres is the identification of atoms and molecules. In hot Jupiter atmospheres, the atoms and molecules identified are atomic sodium (Na) (e.g., Charbonneau *et al.* 2002), water vapor (H_2O) (e.g., Swain *et al.* 2008; Figure 2), methane (CH_4) (Swain *et al.* 2008), carbon monoxide (CO), and carbon dioxide (CO_2) (e.g., Swain *et al.* 2009a,b; Madhusudhan and Seager 2009). (For a critical discussion of Swain *et al.* 2008, see Gibson *et al.* 2011 and Swain *et al.* this volume.) In addition to molecules, the presence of atmospheric haze has been inferred in HD 189733 via transmission spectra with HST/STIS. While the particle composition has not been identified, the Rayleigh-scattering behavior of the data indicates small particle sizes (Pont *et al.* 2008). A thorough temperature and abundance retrieval method enables statistical constraints on molecular mixing ratios and other atmospheric properties (see Fig. 3 and Madhusudhan & Seager, 2009).

3.3. *Day-Night Temperature Gradients*

Hot Jupiters are theorized to have their rotation synchronized with their orbital motion by tidal forces, a process that should conclude within millions of years (e.g., Guillot *et al.* 1996). Under this tidal-locking condition the planet will have a permanent day side and a permanent night side. Spitzer thermal infrared observations of HD 189733b shows that the planet has only a moderate temperature variation from the day to night side. The

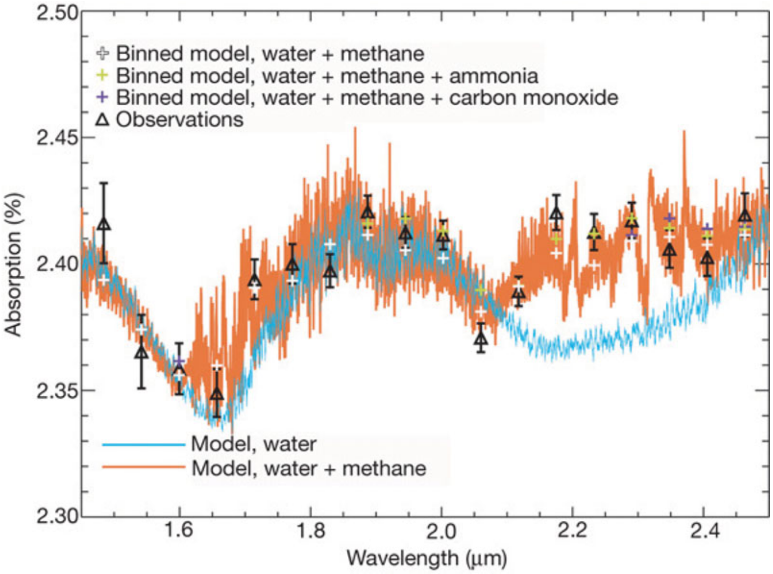

Figure 2. Transmission spectrum of the transiting planet HD 189733. Hubble Space Telescope observations shown by the black triangles. Two different models highlight the presence of methane in the planetary atmosphere. From Swain *et al.* (2008).

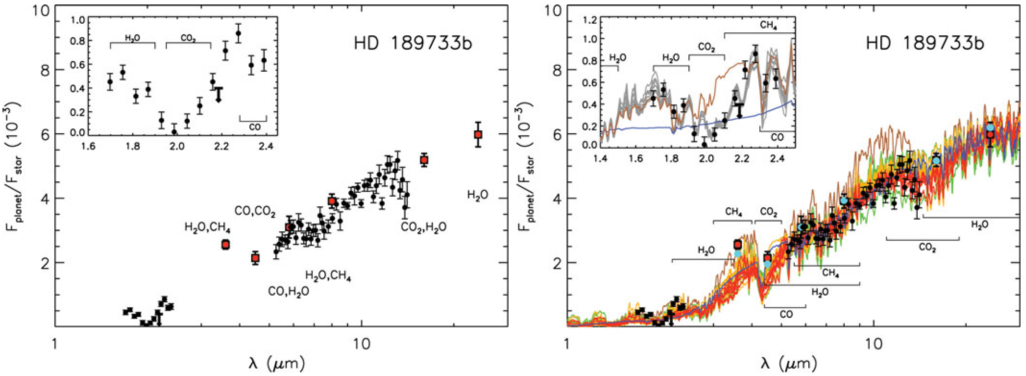

Figure 3. Thermal emission data composite for HD 189733 in secondary eclipse. Data from HST/NICMOS (inset, Swain *et al.* 2009), Spitzer/IRAC (four shortest wavelength red points; Charbonneau *et al.* 2008), Spitzer/IRS-PU (Deming *et al.* 2006), Spitzer/MIPS (Charbonneau *et al.* 2008), Spitzer/IRS (black points from 5 - 13 μm; Grillmair *et al.* 2008). Models shown in the right panel (from Madhusudhan and Seager 2009) illustrate that the best fits to the Spitzer/IRS ((red curve shows fits within the 1.4σ errors, on average; orange 1.7σ, green 2σ, and blue is one best fit model within 1.4σ) and Spitzer photometry (brown curve within 1σ) do not fit the NICMOS data (inset grey curves within 1.4σ) possibly implying variability in the planet atmosphere from data taken at different epochs. For abundance constraints from the different models, see Madhusudan and Seager (2009).

planet shows an 8 μm brightness temperature variation of over 200 K from a minimum brightness temperature of 973±33K to a maximum brightness temperature of 1212±11K (Knutson *et al.* 2007), and a thermal brightness change at 24 μm consistent with the 8 μm data within the errors (Knutson *et al.* 2009). Model interpretation indicates that strong winds have advected the hottest region to the east of the sub-stellar point (Knutson

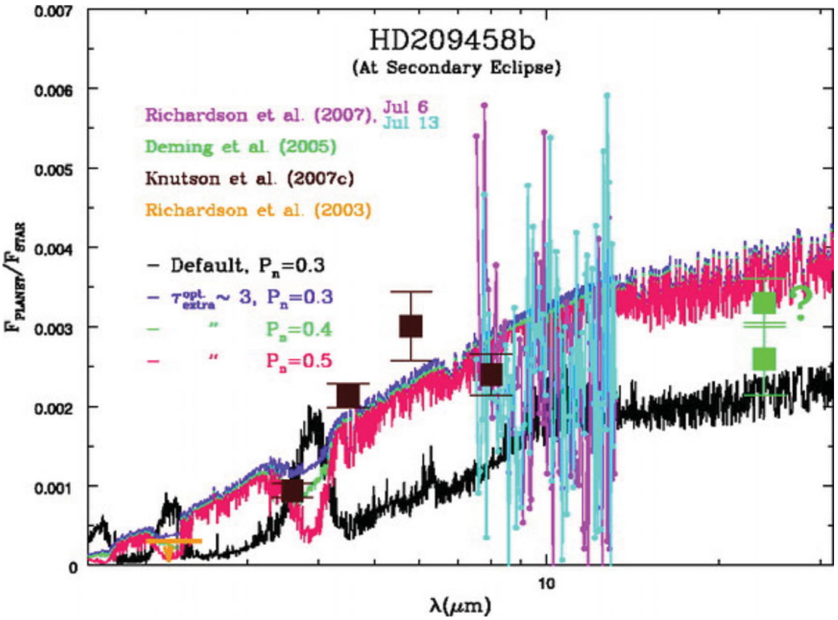

Figure 4. Evidence for an atmospheric thermal inversion for HD 209458b. Spitzer data points from secondary eclipse measurements are shown with brown (IRAC; Knutson *et al.* 2007) and green (Deming *et al.* 2005 and private comm.; the two points are data taken at different times). IRS spectra shown in purple and aqua are from Richardson *et al.* (2007). The model in pink shows emission features from an atmospheric thermal inversion. The black curve is a non-thermal-inversion model. Figure from Burrows *et al.* (2007).

et al. 2007; Showman *et al.* 2009). The shifted hot region on the dayside carries physical information such as the speed of the zonal circulation, and information about the altitude and opacity-dependence of the atmospheric radiative time constant.

3.4. *Atmospheric Escape*

Escaping atomic hydrogen from the exosphere of the hot Jupiter HD 209458b has been detected during transit in the Lyα line. A positive detection was made with HST/STIS (3.75σ) (Vidal-Madjar *et al.* 2003). Showing a 15% drop in stellar Lyα intensity during transit, the HD 209458b observations are interpreted as a large cloud of hot hydrogen surrounding the planet. The cloud extends up to four planetary radii, and the kinetic temperature is as high as tens of thousands of K. Models agree that the implied exospheric heating is likely due to absorption of UV stellar flux, but Jeans escape is not sufficient to account for the hydrogen cloud. The specific origin of the escaping atoms is model-dependent. Escape mechanisms include radiation pressure, charge exchange, and solar wind interaction (see, e.g., Lammer *et al.* 2009 and references therein).

3.5. *Vertical Thermal Inversions*

Evidence for vertical atmospheric thermal inversions in hot Jupiters comes from emission features in place of (or together with) absorption features in the thermal infrared spectrum (for a basic explanation see Seager 2010). Because broad-band photometry does not delineate the structure of molecular spectral bands, the inference of a thermal inversion must rely on models. Spitzer data show that the upper atmospheres of several planets have thermal inversions, if water vapor is present and if abundances are close to solar (e.g., Burrows *et al.* 2008; see Figure 4).

The hot Jupiter temperature inversions are likely created by absorption of stellar irradiance in a high-altitude absorbing layer. Madhusudhan & Seager (2010), however, have found that for many cases existing observations (Spitzer broad-band photometry) are not enough to make robust claims on the presence of thermal inversions.

4. Future Prospects

4.1. *Super Earth Atmospheres*

In exoplanet research the frontier is always the most exciting. In exoplanet atmospheres, the frontier is the field of super Earths. Super Earths are unofficially defined as planets with masses between 1 and 10 Earth masses. The term super Earths should define planets that are rocky in Nature, rather than planets with icy interiors or significant gas envelopes. Because there may be a continuous and overlapping mass range between them, super Earths and "exo-Neptunes" are often discussed together.

The major challenge to studying super Earth atmospheres, is the anticipated wide diversity. This is different from Jupiter and the other solar system gas giants, which have "primitive" atmospheres. That is, Jupiter has retained the gases it formed with, and these gases approximately represent the composition of the sun. The super Earth atmospheres, in contrast, could have a wide range of possibilities for the atmospheric mass and composition. Attempts to evaluate these possibilities used calculations of atmospheres that formed by outgassing during planetary accretion, considering bulk compositions drawn from differentiated and/or primitive solar system meteoritic compositions (Elkins-Tanton & Seager 2008; Schaefer & Fegley 2010). Instead of narrowing down possibilities, this work emphasized the large range of possible atmospheric mass and composition of outgassed super Earths even before consideration of atmospheric escape.

Researchers take different paths for modeling super Earth atmospheres, focusing on different regions of parameter space. One approach is to consider atmospheres similar to Earth, Venus or Mars (or their atmospheres in earlier epochs). Considering the amount of greenhouse gases including CO_2, Selsis *et al.* (2007) and von Bloh *et al.* (2007) both found that Gl 581d is more likely to be habitable (that is with surface temperatures consistent with liquid water) than Gl 581c. Other investigators consider atmospheres that radically depart from the terrestrial planets in our solar system. Water planets, akin to scaled up versions of Jupiter's icy moons, could have up to 50 percent water by mass, with concomitant massive steam atmospheres (Kuchner 2003; Leger *et al.* 2004; Rogers & Seager 2010). In a different approach, Miller-Ricci, Seager, & Sasselov (2009) considered GJ 581c and three possibilities relating to atmospheric hydrogen content. A suggestion of terrestrial planets with sulfur cycles dominating over carbon cycles is described in Kaltenegger & Sasselov (2010). Others have attempted to quantify the atmospheric escape of Earths and super Earths, with little success due to the unknown initial mass and star's activity history (e.g., Lammer *et al.* 2007).

We anticipate the discovery of a handful of rare but highly valuable transiting super Earths in the habitable zones of the brightest low-mass stars. With such targets, we will observe the transiting super Earth atmospheres in the same way we are currently observing transiting hot Jupiters orbiting sun-like stars. NASA's JWST scheduled for launch in 2014, will be capable of observing the absorption signatures of major molecules like water and carbon dioxide. Such observations will require monitoring of multiple transits, often amounting to $\sim$100 hours of JWST observation (Deming *et al.* 2009).

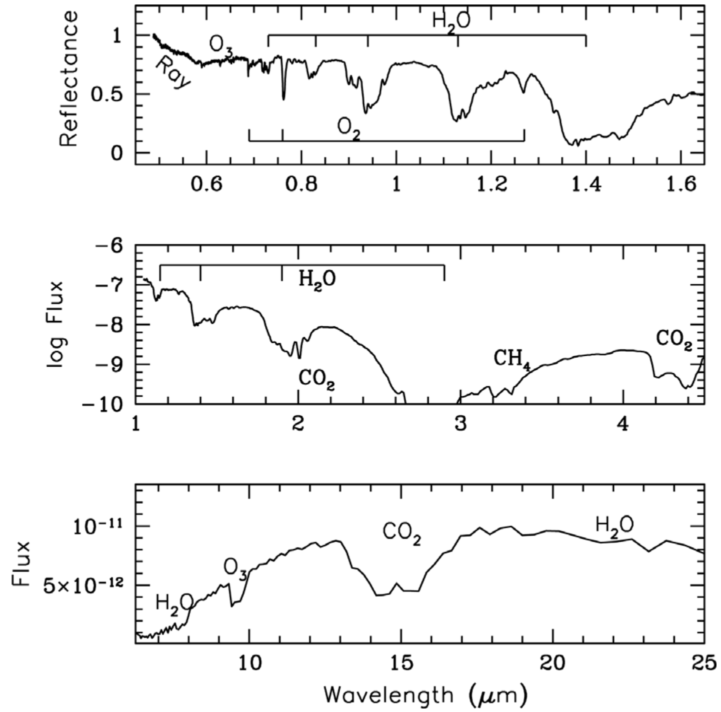

Figure 5. Earth as an exoplanet: Earth's hemispherically averaged spectrum. Top: Earth's visible wavelength spectrum from Earthshine measurements plotted as normalized reflectance (Turnbull *et al.* 2006). Middle: Near-infrared spectrum from NASAs EPOXI mission with flux in units of W m^{2} ?m^{1} (Robinson *et al.*, 2010). Bottom: Earth's mid-infrared spectrum as observed by Mars Global Surveyor enroute to Mars with flux in units of W m^{2} Hz^{1} (Pearl and Christensen 1997). Major molecular absorption features are noted including Rayleigh Scattering. Only strongly absorbing, globally mixed molecules are detectable.

4.2. *Earth Analog Atmospheres and Biosignature Gases*

Without question the holy grail of exoplanet research is the discovery of a true Earth analog, an Earth-size, Earth-mass planet in an Earth-like orbit about a sun-like star. We emphasize that discovery of Earth-size or Earth-mass planets-even those in their star's habitable zone-is not the same as identifying a habitable planet. Venus and Earth are both about the same size and mass-and would appear the same to an astrometry, radial-velocity, or transit observation. Yet Venus is completely hostile to life due to the strong greenhouse effect and resulting high surface temperatures (over 700 K), while Earth has the right surface temperature for liquid water oceans and is teeming with life. This is why, in the search for habitable planets, a direct-imaging space-based telescope capable of blocking out the starlight is inevitable.

The main motivation for finding Earth analogs is to search their atmospheric spectra for biosignature gases. An atmospheric biosignature gas is one produced by life. The canonical concept for the search for atmospheric biosignatures is to find an atmosphere severely out of thermochemical redox equilibrium (Lederberg 1965; Lovelock 1965). Indeed Earth's atmosphere has oxygen (a highly oxidized species) and methane (a very reduced species) several orders of magnitude out of thermochemical redox equilibrium.

In practice it could be difficult to detect molecular features from different redox states. The Earth as an exoplanet, for example (Figure 5), has a relatively prominent oxygen

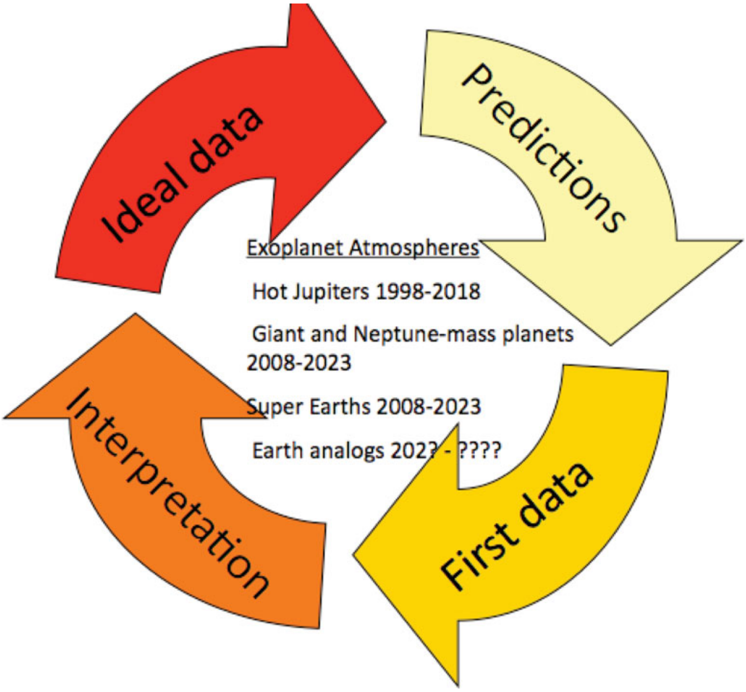

Figure 6. Cycles for exoplanet atmospheres.

absorption feature at 0.76 μm, whereas methane at present-day levels of 1.6 ppm has only extremely weak spectral features. The more realistic atmospheric biosignature gas is a single gas completely out of chemical equilibrium. Earth's example again is oxygen or ozone, about ten orders of magnitude higher than expected from equilibrium chemistry and with no known abiotic production at such high levels. The challenge with a single biosignature outside of the context of redox chemistry becomes one of false positives. To avoid false positives we must look at the whole atmospheric context.

Most biosignatures work to date has focused on mild extensions of exoplanet biosignatures as on Earth (O_2, O_3, N_2O) or early Earth (possibly CH_4) biosignatures. Research forays into biosignature gases that are negligible on Earth but may play a more dominant role on other planets has started. Pilcher (2003) suggested that organosulfur compounds, particularly methanethiol (CH_3SH, the sulfur analog of methanol) could be produced in high enough abundance by bacteria, possibly creating a biosignature on other planets. Pilcher (2003) emphasized a potential ambiguity in interpreting the 9.6 μm O_3 spectral feature since a CH_3SH feature overlaps with it. Segura *et al.* (2005) showed that the Earth-like biosignature gases CH_4, N_2O, and even CH_3Cl have higher concentrations and therefore stronger spectral features on planets orbiting M stars compared to Earth. The reduced UV radiation on quiet M stars enables longer biosignature gas lifetimes and therefore higher concentrations to accumulate. Seager, Schrenk, & Bains (2010) have reviewed Earth-based metabolism to summarize the range of gases and solids produced by life on Earth. A fruitful new area of research will be on which molecules are potential biosignatures and which can be identified as such on super Earth planets different from Earth.

5. Outlook

The field of exoplanet atmospheres is firmly established with a set of hot Jupiter observations and interpretation as the foundation. We see a cycle for atmospheric studies (Figure 6) that begins with predictions at a time when observations are leading theory. Next in the cycle comes the first truly breakthrough observations that enable a flurry of further observations. Third comes a period of interpretation or perhaps more aptly termed retrodiction, modeling and theory work that may raise more questions than answers and beg for better data; this part of the cycle is where observations are leading theory. We are at this point with hot Jupiter atmospheres. Closing the cycle comes when higher S/N and higher spectral resolution data become available to answer the outstanding questions and provide closure. We foresee this closure for transiting hot Jupiters with future JWST observations.

With the cycle picture in mind we envision four eras for exoplanet atmospheric studies. The first is the hot Jupiter studies, with the start of the cycle in 1998 and with at least some closure by five years after JWST launch. The second era is that of more orbitally-distant giant planets and Neptunes, beginning now with direct imaging of young, hot Jupiters far from their stars, maturing with the next generation Gemini and VLT instrumentation, and finding some closure with the very large ground-based telescopes TMT/GMT/ELT of the future. The third era is also just beginning, that of transiting super Earths and mini Neptunes. With large amounts of JWST time the era of super Earths will advance to the third step of the exoplanet atmospheric cycle. The fourth era is that of true Earth analogs. Predictions using Earth as an exoplanet and some extensions are underway, but the first observations will have to await a specialized space telescope that can block out the orders of magnitude brighter starlight.

Thousands of years from now, people will look back and see as one of the most significant, positive accomplishments of our early twenty first century society the first discoveries of exoplanets, and, the human foray into finding and characterizing habitable planets. Exoplanet atmospheres plays a critical component as the hosts of signs of life on other worlds.

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