Highlights of Exoplanetary Science from Spitzer
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ABSTRACT
Observations of extrasolar planets were not projected to be a significant part of the Spitzer Space Telescope’s mission when it was conceived and designed. Nevertheless, Spitzer was the first facility to detect thermal emission from a hot Jupiter, and the range of Spitzer’s exoplanetary investigations grew to encompass transiting planets, microlensing, brown dwarfs, and direct imaging searches and astrometry. Spitzer used phase curves to measure the longitudinal distribution of heat as well as time-dependent heating on hot Jupiters. Spitzer’s secondary eclipse observations strongly constrained the dayside thermal emission spectra and corresponding atmospheric compositions of hot Jupiters, and the timings of eclipses were used for studies of orbital dynamics. Spitzer’s sensitivity to carbon-based molecules such as methane and carbon monoxide was key to atmospheric composition studies of transiting exoplanets as well as imaging spectroscopy of brown dwarfs, and complemented Hubble spectroscopy at shorter wavelengths. Spitzer’s capability for long continuous observing sequences enabled searches for new transiting planets around cool stars, and helped to define the architectures of planetary systems like TRAPPIST-1. Spitzer measured masses for small planets at large orbital distances using microlensing parallax. Spitzer observations of brown dwarfs probed their temperatures, masses, and weather patterns. Imaging and astrometry from Spitzer was used to discover new planetary mass brown dwarfs and to measure distances and space densities of many others.

1. INTRODUCTION
The first detection of a Jupiter-sized planet orbiting a solar-type star with a 4-day period [Mayor & Queloz 1995] carried significant implications for the characterization of exoplanets. It was immediately clear that such planets were likely to be quite hot ($T > 1000$K) due to strong stellar irradiation, and their rotation was likely to be tidally locked to their short period orbits [Guillot et al. 1996]. The combination of large size and high temperature made these “hot Jupiters” very amenable to observations in the infrared (IR) [Seager & Sasselov 2000; Seager et al. 2000]. Indeed, observations of exoplanets - both hot and cold, and both large and small - was a major science theme for Spitzer.

In this paper, we review some highlights of Spitzer’s exoplanetary science, starting with the temperature structure and chemistry of hot transiting exoplanets (Section 2), and continuing with the implications for their atmospheric dynamics (Section 3), and the properties of their orbits (Section 4). Although the majority of exoplanets studied by Spitzer were in transiting systems, Spitzer investigators also used other techniques such as imaging (Section 5.1) and microlensing (Section 5.2). Given that exoplanets overlap the mass range of brown dwarfs, we review highlights of Spitzer’s brown dwarf science in Section 6. We comment on how Spitzer set the stage for the James Webb Space Telescope in Section 7. For a previous review of exoplanetary science using Spitzer, see Beichman & Deming [2018]. Protoplanetary and debris disks are closely related to exoplanets, and disk science from Spitzer is reviewed by Chen et al. [2020] in this review series.

The major techniques that Spitzer used for transiting planets (transits, secondary eclipses, and phase curves) are illustrated in Figure 1. Figure 2 shows a summary timeline, illustrating when some of the important exoplanet milestones occurred during the mission.
2. TEMPERATURE STRUCTURE AND CHEMISTRY

Prior to the launch of Spitzer, the atmospheric chemistry of hot Jupiters was projected to be dominated by water vapor, carbon monoxide, and also (depending on the temperature), methane [Burrows et al. 1997; Burrows & Sharp 1999; Seager et al. 2000; Seager & Sasselov 2000]. The hottest of these planets were expected to have low albedos because they would be too hot for cloud condensation [Sudarsky et al. 2000]. Spitzer confirmed those basic expectations, but variations on the models have been found, as we describe below.

Figure 1. Illustration of the techniques used by Spitzer to measure transiting planets, from Winn [2010]. The occultation is an alternate term for secondary eclipse, and it allows the emergent radiation from the planet to be separated from the star. The depth of the primary transit will vary with wavelength, because molecular and atomic absorptions make the atmosphere effectively more extended at some wavelengths. The brightness of the system as a function of orbital phase is called the phase curve. Note that Spitzer did not spatially resolve any of this structure; the measurements were made using time variations in the total light of the system.

Figure 2. Timeline of some major exoplanetary scientific highlights from Spitzer. Programmatic milestones are illustrated in red, and scientific highlights in blue. Spitzer’s pioneering scientific highlights include detection of hot Jupiter thermal emission via secondary eclipses [Charbonneau et al. 2005; Deming et al. 2005], measurement of phase curves [Harrington et al. 2006; Knutson et al. 2007], the detection of thermal emission from a super-Earth [Demory et al. 2012], measurement of microlensing parallax [Udalski et al. 2015], and defining the architecture of the TRAPPIST-1 system (seven nearly co-planar planets) [Gillon et al. 2017].

2.1. The First Detections of Dayside Emission Spectra

Spitzer was the first telescope to detect the infrared radiation emitted by transiting exoplanets using the secondary eclipse technique. Subtracting spectra or photometry taken during eclipse (planet behind star) from measurements outside of eclipse (star + planet contributing) yielded the emergent spectrum of the exoplanet’s dayside atmosphere.
The first secondary eclipse detections [Charbonneau et al. 2005; Deming et al. 2005] were quickly followed by theoretical interpretations [Barman et al. 2005; Burrows et al. 2005; Seager et al. 2005] and by additional secondary eclipse measurements [Deming et al. 2006]. The earliest measurements focused on hot Jupiters transiting bright stars ($V_{mag} < 8$), such as HD 189733 [Bouchy et al. 2005] and HD 209458 [Charbonneau et al. 2000]. As additional transiting hot Jupiters were discovered by ground-based transit surveys, Spitzer observers used secondary eclipses to construct broadband emission spectra for the dayside atmospheres of these planets.

Those observations were in basic accord with early theoretical models [Burrows et al. 1997; Burrows & Sharp 1999; Seager et al. 2000; Seager & Sasselov 2000] that predicted the emergent spectra of hot Jupiters to be shaped by dominant radiative opacity from water vapor, carbon monoxide, carbon dioxide, and (for cooler and/or carbon-rich atmospheres) methane. Figure 3 shows the agreement between the best available HST Crouzet et al. [2014] and Spitzer observations of HD 189733b Knutson et al. [2009c, 2012]; Kilpatrick et al. [2019] and a cloud-free equilibrium chemistry model with parameterized pressure-temperature profile, solar atmospheric heavy element content (“metallicity”), and carbon to oxygen ratio Zhang et al. [2019]. This planet was one of the earliest transiting hot Jupiters detected and is still one of the most favorable targets known today, and therefore provides a key testing ground for atmospheric models.

In its cryogenic phase, Spitzer had the capability to acquire low-resolution spectroscopy of hot Jupiters at secondary eclipse using the Infrared Spectrograph (IRS, see [Houck et al. 2004]). Due to Spitzer’s modest aperture, IRS eclipse spectra were only possible for the two brightest systems, HD 189733b [Grillmair et al. 2007] and HD 209458b [Richardson et al. 2007; Swain et al. 2008]. The initial results showed primarily continuous spectra, with little evidence for absorption features [Grillmair et al. 2007; Swain et al. 2008]; however Richardson et al. [2007] found tentative evidence for silicate clouds in their spectrum of HD 209458b near 9.65 μm.

Subsequent work on bright hot Jupiters has more completely defined their atmospheric chemistry. For HD 209458b, Spitzer eclipse data in combination with ground-based cross-correlation spectroscopy [Brogi & Line 2019] indicate a composition consistent with solar abundances, and with a carbon-to-oxygen ratio less than unity [Line et al. 2016]. The ultra-hot Jupiter WASP-12b was first observed during Spitzer’s cryogenic phase [Madhusudhan et al. 2011], and seemed to have a carbon-to-oxygen ratio exceeding unity, i.e. it appeared to be carbon-rich ($C/O > 1$). However,
Line et al. [2014] did not find C/O > 1 in a statistically convincing manner using a larger sample from Spitzer that included WASP-12b, and we discuss the C/O issue in more depth in Section 2.3

2.2. A Search for Temperature Inversions

Beyond the basic confirmation that hot Jupiter spectra were shaped by water vapor, carbon monoxide, carbon dioxide, and (in some cases) methane opacity, Spitzer’s secondary eclipse data also provided constraints on the day-side pressure-temperature profiles of these atmospheres. Many early Spitzer investigations reported evidence for the presence of “stratospheres”, otherwise known as temperature inversions, in hot Jupiter atmospheres [Madhusudhan & Seager 2010]. Although the default expectation is for temperature to decrease with increasing height, planets with a temperature inversion have a layer where temperature rises with increasing height. In hot Jupiter atmospheres, these inversions were predicted to be caused by gas phase TiO or VO, which are strong optical absorbers [Burrows et al. 2007, 2008; Fortney et al. 2008; Spiegel et al. 2009; Madhusudhan & Seager 2010]. However, subsequent photometry and spectroscopy of the archetypal inverted atmosphere (HD 209458b, [Knutson et al. 2008]) indicated that it did not in fact host a temperature inversion [Diamond-Lowe et al. 2014; Line et al. 2016]. This change in interpretation was due to improved observing methods (early observations dithered the telescope, which increased the instrumental noise by nearly an order of magnitude) and better instrumental noise models (e.g., Deming et al. 2015). The current consensus based on a handful of planets observed with both Spitzer and HST is that temperature inversions due to TiO and VO do occur in hot Jupiter atmospheres, but only for the most highly irradiated (> 2000 K) planets [Kreidberg et al. 2018; Evans et al. 2017].

2.3. Trends in Atmospheric Composition

During Spitzer’s initial cryogenic mission (Figure 2), it was possible to observe bright transiting planet systems in up to six photometric bands (e.g., Figure 3); despite their low spectral resolution, these data sets nonetheless allowed for reasonably well-constrained inferences about atmospheric composition [e.g., Line et al. 2016; Madhusudhan et al. 2011; Morley et al. 2017a; Stevenson et al. 2014a]. Spitzer observed secondary eclipses for over 100 transiting planets in at least one wavelength band. However, approximately 80% of these planets were not observed until after the end of the cryogenic mission, when the telescope was limited to 3.6- and 4.5 μm IRAC [Fazio et al. 2004] photometry. With only two photometric points there are strong degeneracies between the atmospheric composition and pressure-temperature profile. For example, there can be multiple different combinations of atmospheric structure and composition that provide a comparably good match to the observed spectrum of a given planet. It is nonetheless possible to study the band-averaged brightness temperatures and spectral colors of this larger hot Jupiter ensemble statistically, using methods similar to the color-color diagrams used by stellar astronomers [Triaud 2014; Triaud et al. 2014, 2015; Beatty et al. 2019; Garhart et al. 2020].

One of the strongest conclusions that can be drawn from the total of Spitzer’s secondary eclipses involves the efficiency of longitudinal heat transport by winds. Spitzer observations established that the most strongly irradiated planets circulate heat with the least efficiency, as we discuss in more detail in Section 3.1. In the realm of spectral shapes, Garhart et al. [2020] examined the ratio of the 4.5- to 3.6 μm brightness temperature as a function of planetary equilibrium temperature for a sample of 37 hot Jupiters and found that the 4.5 μm fluxes become more prominent relative to 3.6 μm with increasing stellar irradiance (see Figure 4). This runs counter to predictions from simple solar-composition equilibrium chemistry forward models (e.g., [Fortney et al. 2006]), suggesting that there may be systematic variations in hot Jupiter compositions or vertical thermal structures that are not captured by these models.

Beginning with the Neptune-mass planet GJ 436b ([Stevenson et al. 2010; Lanotte et al. 2014; Morley et al. 2017a]), a series of Spitzer secondary eclipse studies [Kammer et al. 2015; Wallack et al. 2019] have focused specifically on cooler (T_{eq} < 1000 K) transiting planet atmospheres, where methane is expected to replace carbon monoxide and carbon dioxide as the dominant atmospheric reservoir, resulting in a shift in the 3.6- to 4.5 μm spectral slope. At these temperatures, the ratio of atmospheric methane to carbon monoxide and carbon dioxide is predicted to be a sensitive function of atmospheric metallicity and carbon-to-oxygen ratio (e.g., [Moses et al. 2013; Drummond et al. 2019]). For GJ 436b, whose dayside emission spectrum lacks any significant methane absorption and instead appears to have strong inferred CO and CO\textsubscript{2} absorption, the data are best-matched by models with a relatively high (> 200× solar) atmospheric metallicity (e.g., [Stevenson et al. 2010; Moses et al. 2013; Morley et al. 2017a]). When compared to the ensemble of transiting planets with atmospheric metallicity constraints from HST spectroscopy (e.g., [Kreidberg et al. 2014; Wakeford et al. 2017; Spake et al. 2019]), this planet appears to have one of the most metal-rich atmospheres observed to date.
It has long been suggested that the atmospheric compositions of planets should reflect their formation locations and accretion histories. In the solar system, the core mass fractions and atmospheric metallicities of gas giant planets are inversely correlated with their masses (e.g., [Lodders 2003]). Mass and radius measurements for transiting gas giant planets indicate that small (i.e., Neptune-mass) planets also have a greater proportion of heavy elements in their bulk compositions than Jupiter-mass planets [Thorngren & Fortney 2019]. However, it is currently unclear whether or not planets with enhanced bulk metallicities also have enhanced atmospheric metallicities; some models predict that the answer may vary depending on the planet’s migration history [Fortney et al. 2013]. Wallack et al. [2019] investigated trends in the 3.6- and 4.5 µm brightness temperatures of transiting gas giant planets cooler than 1000 K and found no evidence for a solar-system-like correlation between planet mass and atmospheric composition (e.g., [Kreidberg et al. 2014]), but did identify a potential correlation (not statistically secure) between the inferred CH\textsubscript{4}/(CO + CO\textsubscript{2}) ratio and stellar metallicity. These trends will be investigated in much greater detail by JWST, which should provide a definitive answer to this question [Blumenthal et al. 2018; Bean et al. 2018; Schlawin et al. 2018; Drummond et al. 2018].

2.4. Carbon-to-Oxygen Ratio

The ratio of carbon to oxygen in the atmospheres of transiting gas giant planets is also expected to vary with formation location. Protoplanetary disk models predict that the carbon-to-oxygen ratio in the gas should vary with position in the disk, due to spatially different condensation of water and carbon monoxide [Öberg & Bergin 2016; Eistrup et al. 2018]. Hence C/O > 1 in an exoplanetary atmosphere is both plausible and can potentially provide useful constraints on a planet’s formation location and accretion history. The C/O ratio of gas giant planet atmospheres - especially when it exceeds unity - profoundly alters the molecular composition of the exoplanetary atmosphere [Moses et al. 2013; Drummond et al. 2019], and can also impact the thermal structure [Mollière et al. 2015] and cloud properties.
For atmospheres with $C/O > 1$, the water abundance is predicted to drop precipitously, with most of the oxygen being bound in formation of carbon monoxide. The absence of water vapor absorption, which is otherwise expected to dominate the observed spectra of these planets, should be obvious in transit and eclipse spectra, albeit less obvious in Spitzer’s photometry.

The first observational evidence for a high atmospheric $C/O$ ratio was reported by Madhusudhan et al. [2011], who utilized Spitzer’s secondary eclipse photometry to characterize the atmospheric composition of the very hot (2500 K) Jupiter WASP-12b [Hebb et al. 2009]. Stevenson et al. [2014a] subsequently analyzed a more extensive set of Spitzer and HST secondary eclipse data for this planet and concluded that the evidence still favored a carbon-rich composition. However, subsequent studies of this planet’s transmission spectrum [Kreidberg et al. 2015] indicated the presence of a strong water absorption feature, which appeared to run counter to this inferred high $C/O$ ratio. Nonetheless, more recent retrieval studies of the best available secondary eclipse data sets for this planet [Oreshenko et al. 2017] continue to prefer models with relatively high carbon to oxygen ratios. This tension between transmission and emission spectroscopy data serves to highlight some of the intrinsic degeneracies in retrievals based on low resolution spectroscopy and photometry.

![Figure 5. Transmission spectrum for the sub-Saturn mass exoplanet WASP-127b. HST ($< 2 \mu m$) and Spitzer ($> 2 \mu m$) data from Spake et al. [2019] are plotted as black filled circles, while best-fit open-source PLATON models [Zhang et al. 2019] with (blue) and without (red) CO$_2$ opacity are overplotted as solid lines, with uncertainties indicated as colored shading. The band-integrated model values at 3.6 and 4.5 $\mu m$ are shown as horizontal dark red and blue lines. Spake et al. [2019] find that this planet has a super-solar atmospheric metallicity, and that the strong absorption (larger transit radius) in the 4.5 $\mu m$ band can only be matched when carbon dioxide is included in the models. Figure is courtesy of Y. Chachan.](image)

2.5. Transit Spectroscopy

Measurements of the wavelength-dependent transit depths, or “transmission spectra” of transiting planets also provide complementary constraints on their atmospheric compositions. Unlike secondary eclipses, which are strongly
biased towards infrared wavelengths where the planet-star flux ratio is maximized, most transmission spectroscopy studies rely on observations spanning both optical and infrared wavelengths. The overall amplitude of absorption features seen in transmission provides a constraint on the scale height of the atmosphere, which is a function of its mean molecular weight (e.g., metallicity).

Joint spectroscopy from Spitzer and Hubble (and also ground-based spectroscopy in many cases) helped to derive exoplanetary atmospheric metallicities for about a dozen exoplanets to date [Ehrenreich et al. 2014; Stevenson et al. 2014b; Nikolov et al. 2015; Fischer et al. 2016; Wakeford et al. 2017; Alam et al. 2018; Ducrot et al. 2018a; Benneke et al. 2019; Sotzen et al. 2019; Spake et al. 2019]. Because the HST coverage is limited to wavelengths where water is the dominant molecular absorber, Spitzer transit depths provide complementary constraints on absorption from methane, carbon monoxide, and carbon dioxide, all of which absorb strongly in the 3.6 and 4.5 µm bands. Recent observations of the sub-Saturn mass exoplanet WASP-127b shown in Figure 5, from Spake et al. [2019], illustrate the diagnostic power of combined HST and Spitzer data for constraining the abundances of carbon-bearing species. In this case, Spitzer’s transit radius at 4.5 µm could only be matched with strong absorption by carbon dioxide. Benneke et al. [2019] also leveraged Spitzer transit data to show that methane was under-abundant relative to the predictions of equilibrium chemistry models in the atmosphere of the mini-Neptune GJ 3470b.

### 2.6. Thermal Emission from Highly Irradiated Rocky Planets

Rocky exoplanets are much smaller than gas giants, and were therefore difficult targets for Spitzer. However, a subset of these planets orbit extremely close to their host stars [Raymond et al. 2014], resulting in relatively high equilibrium temperatures. Just a few years into its extended warm mission, Spitzer became the first telescope to detect thermal emission from a super-Earth by combining multiple secondary eclipse observations of the ultra-short-period super-Earth 55 Cancri e [Demory et al. 2012]. As of this writing, there is no unequivocal measurement of an atmosphere on an exoplanet that is definitively rocky, but there are intriguing hints. One valuable technique that was pioneered by Spitzer investigators involves photometry of the exoplanet over its full orbit. A so-called phase curve of a rocky exoplanet can in principle reveal the existence of an atmosphere, by demonstrating significant longitudinal heat transport [Seager & Deming 2009]. Application of this method using Spitzer observations of the hot super-Earth 55 Cancri e indicated either an optically thick atmosphere or the existence of low-viscosity surface magma flows [Demory et al. 2016b]. In contrast, the same technique applied to the warm super-Earth LHS 3844b indicated no atmosphere, or only a very thin atmosphere [Kreidberg et al. 2019].

There is also some observational evidence to suggest that the dayside flux from at least one hot super-Earth (55 Cancri e) may vary significantly from orbit to orbit. Demory et al. [2016a] observed a series of eight secondary eclipses of 55 Cancri e at 4.5 µm and found that they varied by a large fraction of their average amplitude. That conclusion was confirmed with an independent analysis of the same Spitzer data by Tamburo et al. [2018]. Tamburo et al. suggest that the planet has a low albedo with inefficient heat redistribution intermittently covered over a large fraction of the substellar hemisphere by reflective grains, which could be produced by volcanic activity or variable clouds.

### 3. ATMOSPHERIC DYNAMICS

Spitzer observers probed the dynamics of (primarily) hot Jupiter atmospheres using several observational techniques: phase curves, eclipse mapping, and searches for variability of secondary eclipse amplitudes.

#### 3.1. Thermal Phase Curves

Arguably Spitzer’s greatest impact on exoplanetary science came through the measurement of thermal phase curves. For tidally locked planets, each orbital phase corresponds to a unique location on the planet, and the measured infrared brightness as a function of orbital phase can be inverted to produce a longitudinal brightness map for the planet (e.g., [Cowan & Agol 2008; Knutson et al. 2009c], and many others cited below). Phase curve studies are also possible for non-transiting planets, but the information content of phase curves is greatest for observations of planets with known radii and orbital inclinations, and most studies have therefore focused on transiting planets. We show a representative 3.6 µm Spitzer phase curve for HD 189733b Knutson et al. [2012] in Figure 6 from [Parmentier & Crossfield 2018] in order to illustrate the relevant geometry.

The earliest phase curve measurements with Spitzer began by combining a few discrete measurements spread over multiple epochs [Harrington et al. 2006; Cowan et al. 2007], but observers quickly realized that continuous phase curve monitoring allowed for both a higher signal-to-noise and more precise correction of instrumental noise sources. The first
full-orbit phase curve of the hot Jupiter HD 189733b [Knutson et al. 2007] spawned a flurry of additional phase curve observations, primarily of hot Jupiters [Knutson et al. 2009c,b, 2012; Cowan et al. 2012; Lewis et al. 2013; Maxted et al. 2013; Lewis et al. 2014; Shporer et al. 2014; Wong et al. 2014; Zellem et al. 2014; Wong et al. 2015, 2016; Krick et al. 2016; Stevenson et al. 2017; Zhang et al. 2018; Dang et al. 2018; Mendonça et al. 2018; Kreidberg et al. 2018; Beatty et al. 2019]. For many of these planets, Spitzer observed full-orbit phase curves in multiple bandpasses (typically just 3.6 and 4.5 µm, but 8.0 and even 24 µm phase curves exist for a few planets, including HD 189733b [Knutson et al. 2012]). In principle, these multi-wavelength observations can be used to characterize the thermal emission spectra and corresponding atmospheric compositions, thermal structures, and cloud properties of these planets as a function of orbital phase [Drummond et al. 2018; Rauscher et al. 2018; Steinrueck et al. 2019]. However, in practice the limited number of bandpasses and relatively broad wavelength ranges of the Spitzer photometric bands make atmospheric retrievals using phase curve data impractical. For a few planets, phase curves using both Spitzer and HST were analyzed to derive their dayside compositions (e.g., [Stevenson et al. 2017; Kreidberg et al. 2018]).

In cloud-free atmospheric circulation models with equilibrium chemistry, both the amplitude of the phase curve and the offset of the peak are sensitive to atmospheric physics [Heng & Showman 2015]. In addition to numerical hydrodynamic models [Showman et al. 2008; Rauscher & Menou 2012; Dobbs-Dixon & Agol 2013; Komacek & Showman 2016; Komacek et al. 2017; Drummond et al. 2018; Tan & Komacek 2019], semi-analytic formulations have also been used to interpret the observations [Cowan & Agol 2011a]. Planets with more efficient day-night circulation are expected to have larger phase offsets and smaller phase curve amplitudes, while those that are closer to radiative equilibrium will have little to no phase offset and relatively large phase curve amplitudes. General circulation models predict that more highly irradiated hot Jupiters should have less efficient heat transport than their more moderately-irradiated counterparts [Perez-Becker & Showman 2013; Komacek & Showman 2016]. While it is true that most strongly irradiated planets have relatively large fractional phase curve amplitudes, there does not appear to be a tight correlation between phase curve amplitude and stellar irradiance [Parmentier & Crossfield 2018]. This may indicate nightside clouds, which mask the signature of thermal emission in cloudy regions and increase the apparent day-night contrast in the Spitzer bands [Keating et al. 2019]. In addition to transport by winds or waves, stellar energy in the most highly irradiated hot Jupiter atmospheres can be removed by dissociation of water vapor and molecular hydrogen on the hot day side [Parmentier et al. 2018; Arcangeli et al. 2018; Lothringer et al. 2018; Tan & Komacek 2019]. Subsequent recombination can release that energy on the night side of the planet [Parmentier & Crossfield 2018; Tan & Komacek 2019], thus augmenting hydrodynamic transport using chemistry. Observations of these ultra-hot Jupiters confirmed a lack of water absorption in their spectra, and revealed thermal inversions in several cases (WASP-18b, WASP-103b, HAT-P-7b [Sheppard et al. 2017; Arcangeli et al. 2018; Kreidberg et al. 2018; Mansfield et al. 2018]).

Phase curve offsets appear to be more tightly correlated with irradiance level than are amplitudes, with the most highly irradiated planets showing relatively small phase offsets [Zhang et al. 2018; Parmentier & Crossfield 2018]. This means that the hottest portion of the day side atmosphere is located close to the substellar point for these planets, whereas in less-irradiated hot Jupiters this hot gas appears to be advected downwind (east) of the sub-stellar point by super-rotating equatorial winds, causing the phase curve to peak prior to the secondary eclipse. This effect was first reported in [Knutson et al. 2007], whose phase curve observation of the hot Jupiter HD 189733b provided observational confirmation for the existence of strong zonal winds on hot Jupiters [Showman et al. 2008]. The size of the offset is diagnostic of the radiative time scale compared to the time for transport of heat by wave motions or advection at the pressures probed by the Spitzer bands [Perez-Becker & Showman 2013; Komacek et al. 2017; Parmentier & Crossfield 2018]. Although most hot Jupiter phase curves have offsets to the east (i.e., super-rotating winds), CoRoT-2b has an offset to the west, possibly due to the presence of patchy clouds or magnetic effects [Dang et al. 2018]. Spitzer phase curves can also be used to look for non-spherical planet shapes due to tidal effects and/or mass outflow. Bell et al. [2019] used phase curve observations to detect ongoing mass loss on the ultra-hot archetype planet WASP-12b. For this planet, the outflowing gas fills and emits within the planet’s Roche lobe, whose solid angle changes as the planet orbits.

Although most hot Jupiters have closely circular orbits due to tidal circularization, a few are in eccentric orbits, with $e$ as great as 0.52 for HAT-P-2b [Lewis et al. 2013, 2014], and 0.93 for HD 80606b [Fossey et al. 2009]. Laughlin et al. [2009] used Spitzer to measure the periastron passage of HD 80606b. They discovered that the planet also has a secondary eclipse (not necessarily true for eccentric transiting planets), and they made a quantitative measurement of the radiative time scale (also, see de Wit et al. 2016).
3.2. **Trends in Atmospheric Circulation Efficiency from Secondary Eclipses**

Secondary eclipses can also provide valuable insights into the longitudinal redistribution of heat on hot Jupiters. Although *Spitzer* observed full or partial phase curves for 26 exoplanets (not all are published yet), it observed secondary eclipses for more than 100 hot Jupiters, in many cases using at least two bandpasses. Cowan and Agol [Cowan & Agol 2011b] demonstrated that the brightness temperatures from these secondary eclipse depths can be used to infer statistical information about the nature of longitudinal heat redistribution and albedos of these planets. These studies indicate that the most highly irradiated hot Jupiters have relatively high dayside brightness temperatures, requiring both low albedos and inefficient day-night circulation, while less irradiated planets appear to have more efficient circulation and/or higher albedos [Schwartz & Cowan 2015; Schwartz et al. 2017; Garhart et al. 2020]. These observations are in good agreement with results from general circulation models, which predict a trend of decreasing circulation efficiency with increasing irradiation [Perez-Becker & Showman 2013; Komacek & Showman 2016].

3.3. **Eclipse Mapping and Variability**

At very high signal-to-noise, secondary eclipse observations can also be used to directly map the dayside brightness distributions of transiting planets. This was first pointed out in pioneering work by Williams et al. [2006], who noted that a non-uniform star-facing hemisphere will cause an apparent time lag on the order of tens of seconds between the observed secondary eclipse phase and the phase predicted for a spatially uniform planet. This time lag was first detected observationally for the hot Jupiter HD 189733b [Agol et al. 2010] with a direction and magnitude consistent with phase curve results for that planet [Knutson et al. 2012]. Taking this phenomenon one step further, the variation in flux as the planet is gradually occulted can be inverted to yield a spatial map of the dayside (star-facing) hemisphere of
the planet [de Wit et al. 2012; Majeau et al. 2012] (not to be confused with phase curves maps covering all longitudes). The hot Jupiter HD 189733b is the only exoplanet whose dayside atmosphere was mapped in this fashion. These initial results [de Wit et al. 2012; Majeau et al. 2012] show an eastward hot spot, consistent with results from phase curve observations. Subsequent improvements in this mapping technique [Rauscher et al. 2018] confirmed this basic result.

In the temporal domain, observers monitored secondary eclipses of the two brightest transiting hot Jupiter systems (HD 189733b and HD 209458b) to search for possible temporal variability [Agol et al. 2010; Kilpatrick et al. 2019]. The observed upper limits ($\lesssim 6\%$) are several times greater than predictions from hydrodynamic models [Komacek & Showman 2019].

4. PROPERTIES OF ORBITS

4.1. Eccentricities

Spitzer’s precise transit and secondary eclipse observations can also be used to probe the orbital properties of exoplanetary systems. It has been suggested that hot Jupiters may have formed at much larger orbital separations and then migrated inward via disk integration or high eccentricity migration and circularization [Dawson & Johnson 2018]. Because tidal circularization is predicted to be slow, the frequency of residual non-zero eccentricities for hot Jupiters (as a function of semi-major axis) can in principle constrain the likelihood of a high eccentricity migration channel [Dawson & Johnson 2018]. However, there are multiple ways for a planet to acquire a non-zero orbital eccentricity (planet-planet scattering, secular dynamics, disk interactions, etc.). To distinguish between the signatures of various mechanisms, sensitivity to small orbital eccentricities ($e \sim 0.01$) is desirable, but difficult to achieve using radial velocity observations alone. Fortunately, secondary eclipse timing observations from Spitzer (in combination with radial velocities) yielded precise eccentricity estimates [Deming et al. 2007; Blecic et al. 2013; Lewis et al. 2013; Knutson et al. 2014], and limits on eccentricity [Knutson et al. 2009a; Todorov et al. 2010; Deming et al. 2011] for hot Jupiters. Spitzer’s secondary eclipse times often give $e \cos \omega$ to a precision better than 0.01, but not $e$ directly. However, the argument of periastron ($\omega$) should be distributed randomly, hence secondary eclipse times are statistically useful to define the residual eccentricity distribution as a function of semi-major axis. Those statistical studies are just beginning [Garhart et al. 2020], but there are ample Spitzer eclipse data that can be utilized, especially when orbital ephemerides can be improved using TESS transits.

Beyond statistical studies, Spitzer was instrumental in probing the properties of individual planets. We here highlight two examples: the interior structure of HAT-P-13b, and the orbital decay of WASP-12b.

4.2. The Core Mass of HAT-P-13b

The HAT-P-13 system comprises a hot Jupiter (HAT-P-13b) and two companion planets with much longer orbital periods, one of which has an eccentric orbit [Winn et al. 2010b]. That particular orbital configuration will produce a slight eccentricity in the orbit of HAT-P-13b, and the magnitude of that eccentricity depends on its internal mass distribution, specifically on the core mass [Batygin et al. 2009]. This is a key question for formation models, but while it is possible to constrain the bulk metallicities of hot Jupiters using masses and radii [Thorngren & Fortney 2019], these observations do not provide information about the relative distribution of these metals between the core and envelope. Radial velocity observations [Winn et al. 2010b] indicated a small non-zero eccentricity for HAT-P-13b. Secondary eclipse times using Spitzer confirm a small eccentricity, but the core mass is sensitive to the exact phase of the eclipse. Buhler et al. [2016] find a probable core mass of about 11 Earth masses, whereas Hardy et al. [2017] concluded that the core is small or non-existent, but they note that their eclipse times are significantly inconsistent (differing by 23 minutes) between the two Spitzer bandpasses. Independently measured eclipse times from Garhart et al. [2020] are internally consistent and agree with Buhler et al., thereby supporting the 11 Earth mass core estimate.

4.3. The Orbital Decay of WASP-12b

The orbits of hot Jupiters should be decaying as tidal dissipation removes energy from their orbits. For hot Jupiters with the shortest known periods, the orbital decay is astrophysically fast, but long on a human time scale. Nevertheless, Spitzer made orbital decay possible to observe in the case of WASP-12b, a very close-in and ultra-hot Jupiter. Patra et al. [2017] found that the orbital period was apparently decreasing by $29 \pm 3$ milli-seconds per year, based on ground-based transits and Spitzer secondary eclipses. However, they could not rule out apsidal precession, wherein the orientation of the orbit within the orbital plane changes, but the orbital period remains constant. Fortunately, secondary eclipses could distinguish these possibilities, and Spitzer secondary eclipses [Yee et al. 2019] confirmed the
Figure 7. Transit and secondary eclipse (occultation) times for WASP-12b, showing orbital decay, from Yee et al. [2019]. The upper panel shows residuals of transit times from a linear ephemeris; the curvature shows that the period derivative is not zero. The lower panel shows timing residuals for primarily Spitzer’s secondary eclipses, and models for orbital decay versus apsidal precession. Orbital decay is highly favored over apsidal precession.

decrease of the orbital period, as shown in Figure 7. The results give insight into the physics of tidal dissipation, specifically the Q-factor [Goldreich & Soter 1966] of the star (the dissipation occurs within the star). Yee et al. [2019] find a Q-factor of $1.75 \times 10^5$, which is lower than many previous (but less direct) determinations. Yee et al. also use new radial velocity data to prove that the observed acceleration is not due to changes in light travel time caused by a companion planet in a long period orbit.

4.4. Systems of Planets

Spitzer was especially valuable in searching for transits of planets orbiting M-dwarf stars, because M-dwarfs are bright in the IR. The M-dwarf star GJ 1214 hosts a transiting mini-Neptune [Charbonneau et al. 2009], orbiting closer to the star than the nominal habitable zone (HZ). Fraine et al. [2013] and Gillon et al. [2014] searched for planets in the inner HZ of GJ 1214, and placed Mars-sized upper limits on the presence of such planets. However, the largest payoff for Spitzer was the delineation of multiple transiting planets orbiting the ultra-cool M-dwarf system TRAPPIST-1. Discovered by the ground-based TRAPPIST survey [Gillon et al. 2016], a long-duration quasi-continuous sequence of Spitzer photometry [Gillon et al. 2017] revealed a system of 7 rocky planets, all transiting the small M-dwarf star (Figure 8). Exoplanetary scientists have already begun characterizing the atmospheres of these worlds [de Wit et al. 2018; Ducrot et al. 2018b], but no unequivocal atmospheric detections have yet been achieved. Their atmospheric transmission spectra are predicted to (potentially) contain absorption features from molecular oxygen, ozone, water vapor, sulphur dioxide, carbon monoxide, and methane [Lincowski et al. 2018; Hu et al. 2020], and it is possible that the planets may be tidally heated [Dobos et al. 2019], or heated inductively via the stellar magnetic field [Kislyakova et al. 2017]. There is enormous community interest in the TRAPPIST-1 planets, and they are expected to be important targets for JWST [Morley et al. 2017b; Lustig-Yaeger et al. 2019].

4.5. Transit Timing Variations in the TRAPPIST-1 System

When multiple planets are present in a system, their mutual gravitational perturbations produce transit timing variations (TTVs), manifest as departures from a strictly linear ephemeris [Holman & Murray 2005]. Those TTVs can be used, in conjunction with a dynamical model, to infer the masses of the planets [Agol & Fabrycky 2018]. In many cases, TTVs are the only practical method to derive exoplanet masses because small planets often produce a radial velocity signal in the stellar spectrum that is too small to measure. In contrast, TTVs can be readily measured,
Figure 8. Transits of planets in the TRAPPIST-1 system as observed with Spitzer and ground-based photometry, from Gillon et al. [2017]. The upper two panels (a and b) show the photometry, with colored symbols marking transits of the various planets. The lower left panel (c) shows the phased transits of all seven planets, and the lower right panel (d) shows their orbits.

especially using long continuous photometric sequences from Spitzer. In the case of multi-planet systems such as TRAPPIST-1, mutual occultations among the planets can help to extract precise TTVS [Luger et al. 2017]. Delrez et al. [2018] and Grimm et al. [2018] analyzed 60 and 284 transit times, respectively, for the TRAPPIST-1 system, and Grimm et al. derived masses with precisions between 5% and 12%. They used those masses to infer that two of the planets were predominately rocky, while the remaining five have low density envelopes such as atmospheres, oceans,
or layers of ice (also, see Dorn et al. 2018). Those inferences are valuable in planning atmospheric characterization studies of the system using JWST.

4.6. Planetary Radii and Orbital Periods

The first benefit of a primary transit is to obtain a precise radius for the transiting exoplanet, and accurate radii are fundamental for characterizing exoplanetary properties. Stellar limb darkening is greatly reduced in the IR compared to optical wavelengths. Consequently, Spitzer’s transits tend toward simple box-like shapes, and yield the ratio of planet-to-star radius in a simple and minimally model-dependent manner, albeit with potentially higher random noise due to reduced stellar photon fluxes in the IR [Richardson et al. 2006; Nutzman et al. 2009; Gillon et al. 2012]. The high cadence and uninterrupted photometry available from Spitzer were crucial for precise transit measurements [Demory et al. 2011; Ballard et al. 2014; Chen et al. 2018], especially when the transit had a long duration [Hébrard et al. 2010]. Moreover, star spots and plage - which can potentially interfere with accurate radius measurements - have low thermal contrast with stellar photospheres in the IR [Fraine et al. 2014; Morris et al. 2018], further increasing the utility of Spitzer’s measurements of exoplanetary radii. Although solar-type stars are not as bright in the IR as in the optical, M-dwarf stars provide high fluxes in Spitzer’s bands, allowing precise radii for their (sometimes small) transiting planets [Gillon et al. 2007; Fraine et al. 2013; Gillon et al. 2016; Chen et al. 2018].

After a transiting planet is discovered, imprecision in its orbital period leads to an accumulating error in the times of transit and eclipse as time passes. In order to observe transiting planets with JWST, it is necessary to have accurate orbital periods, and Spitzer played a key role in that effort. Follow-up of Kepler and K2 planets, for example, was possible with Spitzer, improving the orbital periods and in some cases measuring TTVs [Beichman et al. 2016; Benneke et al. 2017; Berardo et al. 2019; Dalba & Tamburo 2019; Livingston et al. 2019].

5. OTHER TECHNIQUES

Although the majority of exoplanets studied by Spitzer were in transiting systems, the observatory also enabled significant work using other techniques such as high contrast imaging and microlensing.

5.1. High Contrast Imaging

Spitzer’s modest aperture provided relatively low spatial resolution: the diffraction-limited full-width-to-half-maximum of point sources is 1.3 seconds of arc at 4.5 µm wavelength. Nevertheless, Spitzer had excellent sensitivity to low flux levels at thermal wavelengths where young, hot planets will emit. That motivated searches for giant planets at large orbital distances. Those searches included specific bright stars such as Vega, Fomalhaut, and Epsilon Eridani [Janson et al. 2015], as well as larger samples of young stars, including many host stars of known exoplanets [Durkan et al. 2016]. Although Spitzer did not detect any new exoplanets by imaging, the surveys provided important constraints on planet formation at distances between 100 and 1000 AU [Durkan et al. 2016].

In addition to exoplanet imaging searches, observers also used Spitzer to discover and investigate especially interesting companions in the brown dwarf mass range. Leggett et al. [2010] obtained IRS spectroscopy of a T8 brown dwarf in a binary system with an M-dwarf star. They used this spectrum to place constraints on the surface gravity, inferring a mass between 24 and 45 Jupiter masses. Luhman et al. [2011, 2012] found a very cool companion to the white dwarf WD 0806-661 with a temperature of 300 K and a corresponding mass of approximately 7 Jupiter masses.

5.2. Microlensing

Even prior to the launch of Spitzer, it was anticipated to be an important facility for microlensing [Gould 1999]. Spitzer’s continuous and nearly uninterrupted viewing enable photometry that can define the structure of microlensing events, and thereby determine the nature of the lensing systems, including the presence of planets. Microlensing has a unique ability to detect small planets at large orbital distances, inaccessible to other techniques [Gaudi 2012]. Accurate photometry is difficult in the crowded fields that are used for microlensing searches. Nevertheless, the microlensing studies were productive in finding planets in parts of the galactic disk [Street et al. 2016] and bulge [Ryu et al. 2018] at distances of several kiloparsecs. Moreover, Spitzer’s drift-away orbit gives it a view of microlensing events over a long spatial baseline when combined with observations from the ground [Shvartzvald et al. 2017], or from another spacecraft [Shvartzvald et al. 2016]. An example of the photometrically different view of a microlensing light curve by Spitzer is illustrated in Figure 9, from Calchi Novati et al. [2019]. The different view from Spitzer permits the measurement of the microlensing parallax [Gould 1999; Udalski et al. 2015], from which the masses of the lensing star and planet (not merely their ratio), and their projected orbital separation, can be determined.
Results from Spitzer’s microlensing campaigns include both giant planets [Calchi Novati et al. 2019] as well as low mass planets approaching the mass of Earth [Gould et al. 2019]. Shvartzvald et al. [2017] point out that, together with the TRAPPIST-1 system, their microlensing detection of a 1.4 Earth-mass planet orbiting an ultra-cool M-dwarf star suggests that systems of rocky planets may be common around ultra-cool M-dwarf stars. The ultimate goal of the microlensing studies is to understand the frequency of occurrence of exoplanets in different regions of the Galaxy, and Spitzer made significant advances toward that goal [Dang et al. 2019].

6. BROWN DWARFS

Beyond exoplanets, Spitzer also advanced the study of brown dwarfs. These substellar objects can overlap with giant exoplanets in mass, but even when found in orbit around a more massive star they are believed to be a separate population. Most planets and brown dwarfs form by different mechanisms, but massive planets are sometimes found at orbital distances of 100’s to 1000’s of AU [Nielsen et al. 2019; Bowler et al. 2020], and those planets may form in a similar manner as brown dwarfs [Kratter & Lodato 2016; Kouwenhoven et al. 2020].

Spitzer’s brown dwarf investigations can be broadly divided into several sub-topics. First, Spitzer measured parallaxes for brown dwarfs, which made it possible to determine fundamental properties such as mass. Second, Spitzer mapped the nature of their emergent spectra, helping to extend the stellar spectral sequence to lower mass objects (L, T, and Y spectral classes). Spitzer observers also mapped weather on brown dwarfs via their rotational light curves. We discuss these topics in more detail below. Moreover, Spitzer imaging was used to discover new brown dwarfs, often as companion to brighter stars, and those cases are discussed in Section 5.1.

6.1. Parallaxes and Proper Motions

When studying brown dwarfs, measurements of common proper motion in binary systems and distances via parallax are often crucial. Observers exploited the long time baseline and varying orbital position of Spitzer to make both common proper motion [Luhman et al. 2012] and parallax measurements [Kirkpatrick et al. 2013; Martin et al. 2018; Kirkpatrick et al. 2019] for brown dwarfs, sometimes in combination with HST and/or the WISE mission [Beichman et al. 2014]. Spitzer’s parallax measurements for Y-dwarfs are especially important [Martin et al. 2018; Kirkpatrick
et al. 2019], because distances are crucial for inferring properties such as mass. For example, Leggett et al. [2017] determined that the coldest known Y-dwarf (WISE 0855-0714, $\sim 250$ K) has a mass between 1.5 – 8 Jupiter masses, based on a Spitzer parallax that enabled comparison with evolutionary models. Spitzer parallaxes [Kirkpatrick et al. 2019] were critical to determining the mass function of brown dwarfs, and showing that the low mass cutoff for their formation is probably less than 5 Jupiter masses. This indicates overlap between the core accretion and disk fragmentation populations in a low mass range.

6.2. Emergent Spectra of Brown Dwarfs

Brown dwarfs give us the opportunity to study and model the spectra of Jovian-mass objects without the complexity of starlight rejection by either coronagraphy or transits, or the atmospheric reaction to strong stellar irradiation. They thereby offer a laboratory for atmospheric modeling and comparison to models used for core accretion systems. Brown dwarf spectroscopy is thereby expected to be an important topic for JWST [Morley et al. 2019].

In Spitzer’s cryogenic phase, Roellig et al. [2004] used IRS to obtain spectra of an M, L, and T dwarf (one in each class). Although water vapor absorption was present in those spectra, the highest absorption was by methane in the band at 7.8$m\mu$, and also the first detection of ammonia absorption (near 10.5$m\mu$). Subsequent studies using larger samples of brown dwarfs [Cushing et al. 2006; Leggett et al. 2009] showed that absorption by methane and ammonia appears at the L/T transition, with signatures of silicate and iron condensate clouds also being common for L and T dwarfs. Saumon et al. [2006] studied ammonia absorption in a T7.5 dwarf, and could only account for the spectrum by reducing the ammonia abundance approximately one order of magnitude below a chemical equilibrium model. They attributed their result to disequilibrium caused by vertical mixing. Extending brown dwarf studies to the Y dwarfs, Leggett et al. [2017] also concluded that vertical mixing is important, and they derived effective temperatures, surface gravities, and metallicities for four Y-dwarfs with temperatures close to 600 K.

In addition to IRS spectra, photometry using IRAC [Patten et al. 2006; Burningham et al. 2013; Leggett et al. 2017] defined the position of brown dwarfs in color-magnitude and color-color diagrams. Although studying brown dwarf colors was not new per se, Spitzer’s sensitive observations in new wavelength bands produced a new perspective on the colors of brown dwarfs. These studies show that not only temperature, but also mass (via surface gravity) and metallicity affect brown dwarf colors, and they again found that departures from chemical equilibrium are important [Leggett et al. 2017]. Comparing brown dwarfs to hot Jupiters, Beatty et al. [2014] found that isolated brown dwarfs have colors that are very similar to the hot Jupiters and to the irradiated brown dwarf KELT-1b.

Brown dwarfs can be highly variable in their thermal emission. Esplin et al. [2016] used IRAC photometry to find variability in the IR emission of WISE 0855-0714. Morales-Calderón et al. [2006] used IRAC photometry in a pioneering search for photometric variability due to weather patterns on rotating brown dwarfs. Variability of brown dwarfs was subsequently detected in ground-based observations [Artigau et al. 2009]. Investigations using Spitzer in combination with HST and/or ground-based photometry exploited different heights of formation versus wavelength for powerful probes of inhomogenous cloud patterns as brown dwarfs rotate [Buenzli et al. 2012; Apai et al. 2013; Yang et al. 2016; Leggett et al. 2016; Biller et al. 2018]. Spitzer’s capability for long uninterrupted observational sequences was key to studying variability of brown dwarfs. The magnitude of variability is a function of the viewing angle (pole versus equator [Vos et al. 2017]), and the largest variations are seen when the line of sight is near-equatorial. For example, Biller et al. [2018] observed the full amplitude of variability in the young planetary-mass object PSO J318.5-22 using IRAC 4.5$m\mu$ in combination with HST at 1.1-1.7$m\mu$. They found a large phase offset between the Spitzer and HST wavelengths, attributed to different longitudinal cloud structures at different pressures (each layer has a distinct temperature and corresponding infrared emission). The rotational variations can be complex, and the patterns can vary on time scales longer than the rotational period [Apai et al. 2017].

Apai et al. [2017] analyzed long term IRAC photometry to infer the presence of planetary-scale wave features and discrete spots on 2MASS J21392216+0220185, illustrated on Figure 10. They infer the presence of bands whose brightness varies longitudinally (e.g., from variations in cloud opacity). The rotational period differs slightly from band to band, due to zonal winds. Those different periods cause a beating effect that is revealed in the Spitzer photometry. Spitzer observers have thereby demonstrated a rich dynamic meteorology in brown dwarf atmospheres. The Spitzer results stimulate interest in continuous spectral monitoring with high sensitivity using JWST. Finally, we note that brown dwarf meteorology is similar to variable bands seen on Neptune and Jupiter [Apai et al. 2017], illustrating a link between low mass brown dwarfs and planets.

7. THE STAGE IS SET FOR JWST
Figure 10. Spitzer IRAC photometry of 2MASS J21392216+0220185, from Apai et al. [2017]. The top panel shows the photometry (blue points = 3.6 $\mu$m, red points = 4.5 $\mu$m), and the lower panel shows the retrieved model having three bands and a spot. Due to zonal winds, the bands have different rotation periods, and beat against each other in the integrated light.

7.1. Operational Legacy

The Spitzer Science Center (SSC), in partnership with the broader exoplanet community, pioneered many innovative operational techniques to maximize the scientific yield of the mission for exoplanetary science. Those innovations include improvements in the duration of observational sequences and in data compression [Carey et al. 2011], mitigation of pointing fluctuations [Carey et al. 2011; Ingalls et al. 2012; Carey et al. 2014; Grillmair et al. 2014], and the development of novel techniques to remove instrumental noise [Ingalls et al. 2018]. Frequent interactions between observers and the SSC culminated in a “data challenge” to test a multitude of methods for precise and accurate correction of instrumental noise sources in IRAC photometry [Ingalls et al. 2016]. Those efforts influenced plans for JWST’s Early Release Science program [Bean et al. 2018], and we expect that the operational lessons from Spitzer will be an enduring legacy for JWST.

7.2. Scientific Legacy

Without observations from Spitzer, the potential for exoplanetary science from JWST would be far less clear. Spitzer defined the magnitude of infrared emission from hot Jupiters, constrained the nature of their emergent spectra, and
sharpened the questions concerning their atmospheric physics and chemistry. Spitzer’s sensitivity to carbon-bearing molecules was a prelude to the new insights that will be possible from JWST’s panchromatic spectra. The spectra of hot Jupiters change in response to stellar irradiation in ways that we currently do not fully understand, and their phase curves exhibit an interplay between radiative heating, cooling, and cloud formation that challenges our hydrodynamic models. Beyond hot Jupiters, Spitzer probed Neptunes and super-Earths, finding new phenomena such as disequilibrium chemistry and puzzling variability in day side emissions. In the study of brown dwarfs, Spitzer measured weather patterns via rotational variability. Spitzer also discovered new ultra-cool brown dwarfs and characterized their emergent spectra, distances, and space densities.

Observations from Spitzer also probed the orbital dynamics of close-in exoplanets, with implications for the internal structure of the planets and their host stars. Spitzer mapped planetary systems such as TRAPPIST-1, and measured masses using TTVs. Spitzer’s observations opened multiple sub-disciplines of exoplanetary science, to a degree not dreamed of before its launch. JWST will begin with a rich menu of fascinating questions that are the legacy of exoplanetary science from Spitzer.

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