Spectral variability of Earth-like planets

A further step is to use narrow band data to build the spectral signal of Earth-like planets. By the comparison with spectra of terrestrial planets, we can infer the physical conditions of the atmosphere, the state and abundances of the main atmospheric species, as well as the global parameters of the planetary climate. The study of narrow-band light curves will also give an important information about the dynamics and the evolution of the most relevant compounds. By the average of the signal, we can also build longitudinal light curves and study their distribution on the planet. We have used a new generic version of the LMD Global Climate Model to build the spectral light curves of the Earth-like planets studied in Chapter 5: the Earth, the Earth with a rotation rate of 10 days (Ete–10), the aquaplanet Ote–1 and the snowball aquaplanet SOte–1.

7.1 Detection of Earth-like planets

The Earth has a brightness temperature of ∼255 K, and the correspondent blackbody emission has a peak at ∼11 μm. Then, the thermal infrared (5-20 μm) is the most favorable spectral range to detect Earth-like planets. The orbital parameters can be detected by radial velocity using high-resolution spectrometers. For an Earth analogue at a distance of 1 UA from a solar-type star, the flux contrast factor between the star and the planet F_*/F_{pl} is $\simeq 10^6$, 1000 times larger than in the visible range, however in order to obtain an angular distance above the difraction limit $\lambda/D \sim$ 100 mas, a diameter D of 40 m for ground-telescopesis required (**?**). The spectral features of H_2O,CO_2, and O_3 are detectable, however CH_4 is just detectable in Early-Earth atmospheres where CH_4 is predominant (Table 7.1). In the case of rocky

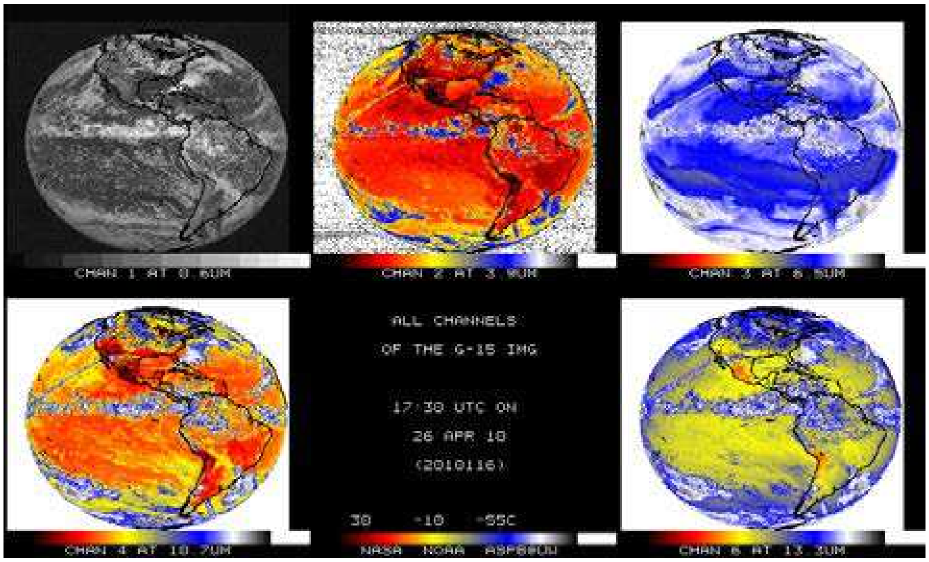

Figure 7.1 NOAA newest Geostationary Operational Environmental Satellite (GOES-15) took its first imager full-disk infrared image of the Earth on April 26 starting at 17.30 UT. Each of the five imager spectral bands are shown. There is one visible band and four infrared bands (shortwave window, water vapor, longwave window and a CO_2 sensitive band). Credit: NASA-NOAA-SSEC.

planets around cold dwarf stars of masses between 0.1-0.2 $M_\odot$ the detection from the ground is possible by 4-8 *m* class telescopes for planets at a maximum distance of $\simeq$50 *pc*, with the use of a telescope of 40 m as E-ELT (Martín & Guenther, 2006) allows to acheive distances up to $\simeq$200 *pc* (e.g., Oliva & Origlia, 2008; Pallé et al., 2011). Furthermore, we can increase the S/N ratio, using instruments like HIRES and METIS on grounds-based telescopes like E-ELT, which will open the door to a new range of measurements:

i) High-resolution spectra.– Planetary spectra can be used to probe into the atmosphere of the planet by identifying the optical depths as they depend directly on wavelength. Features on the atmosphere can be then separated with a resolving power of R$\sim$300, and used to recover the abundances, state, distribution and dynamics of atmospheric species.

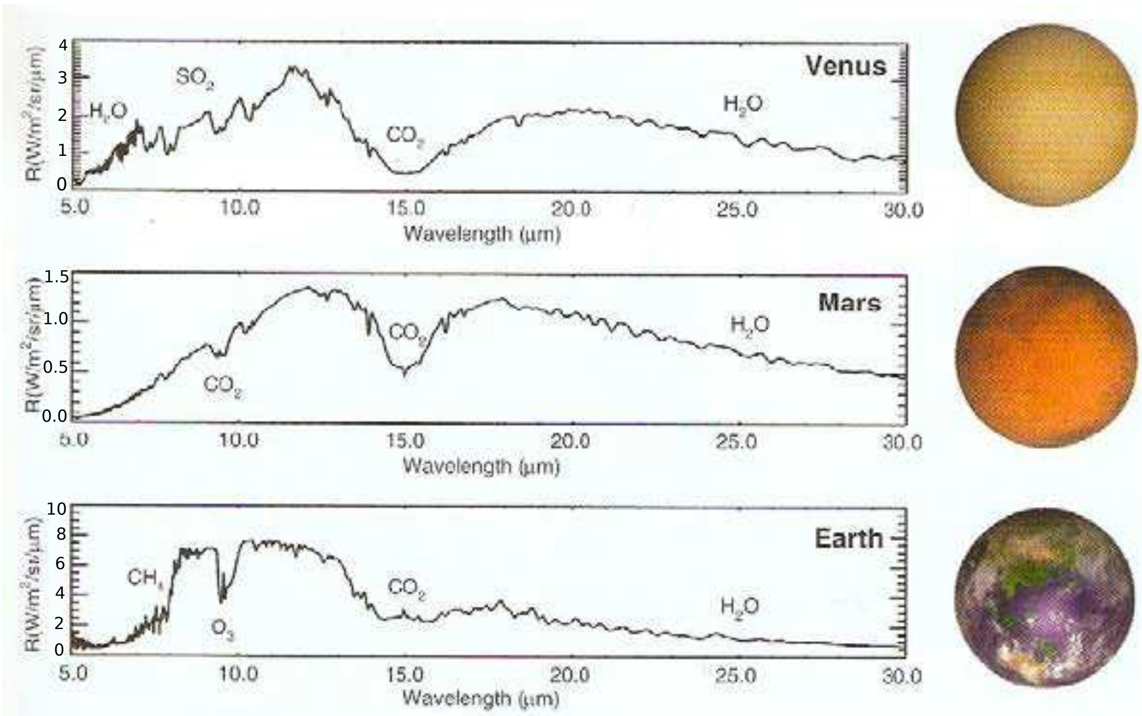

Figure 7.2 Spectral radiance of Venus, Mars and the Earth. (From Vázquez et al. 2010).

ii) Rotation rate and winds.– Orbital velocity maps (time vs. orbital velocity) can be used to measure the zonal winds and the rotation rate of the planet. The velocity deviation is clearly shown as a line broadening (Snellen et al., 2010).

iii) Longitudinal spectral variations.– We can build averaged rotational light curves as a function of the planetary longitude (Section 2.3.2, Figure 5.18 and Figure 6.12) to illustrate the distribution and the dynamics of atmospheric compounds.

Future space telescope missions will use the transit method on bright stars to detect Earth-like planets: PLATO (Catala & PLATO Consortium, 2008; Rauer & Catala, 2011), an ESA mission that is previewed to be launched in 2017-2018, will

Table 7.1. Detection of atmospheric spectral features

Gas	Terrestrial abundance	Spectral feature (μm)	Resolution	Detection threshold
H_2O	8000 ppm	19.6	3.3	1 ppm
CO_2	355 ppm	15	4	1 ppm
O_3	6 ppm	9.6	17	1 ppm
CH_4	2 ppm	8	6	10 ppm
NO_2	0.1-1 ppb	6.3	30	100 ppb
NH_3	0.01 ppb	11	10	10 ppm

Note. — Thermal IR spectral features of the main atmospheric gases on Earth-like planets. The detection threshold is calculated assuming a spectral resolution of 20 and a S/N of 10. From Ollivier et al. (2008); Des Marais et al. (2002) and Selsis et al. (2007).

search transits around stars of 8-11 magnitudes; TESS (e.g., Ricker et al., 2009) is a NASA mission for stars fainter than 12 magnitudes and it will be operative in 2017. EChO (e.g., Tinetti et al., 2012) is the first space mission designed to study exoplanet atmospheres and it will provide high-resolution multiwavelength spectroscopic observations in the infrared range (0.4-11) μm with a contrast ratio $F_*/F_{pl}\sim 10^5$.

A solution to improve the observations without building large telescopes is to use the nulling interferometry technique (Bracewell, 1978), either by a structurally connected interferometer or by a flagship mission, with a 2 m diameter collectors will be capable of detecting more than 100 Earth size planets around nearby stars. However space projects as SIM (e.g., Tanner et al., 2006; Catanzarite et al., 2006; Tanner et al., 2010), DARWIN (e.g., Ollivier et al., 1999, 2001; Cockell et al., 2009) and TPF-I (e.g., Kaltenegger & Fridlund, 2006; Gappinger et al., 2007) have been cancelled.

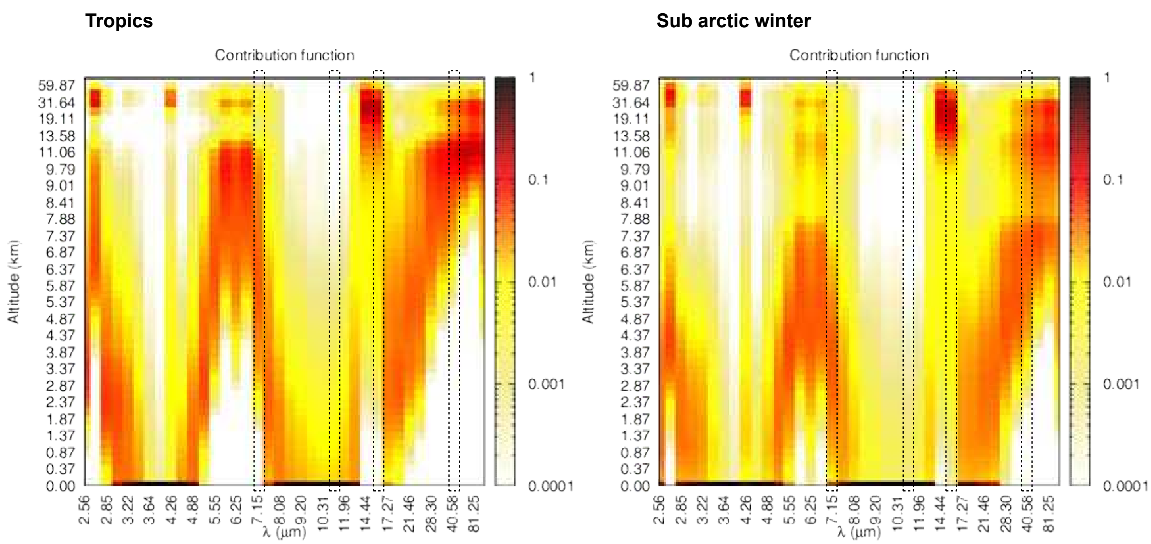

Figure 7.3 Contribution functions for the tropics (left) and the subartic winter (right). The rectangles show the layers that contribute to the formation of the bands used in Figs. 7.4–7.7.

7.2 Climate Model

The generic model was developed at the Laboratoire de Météorlogie Dynamique (LMD) to explore a broad range of conditions in terms of temperature, pressure, atmospheric composition. Its aim is the study early climates (Forget et al., 2013; Wordsworth et al., 2013) and exoplanet atmospheres (Wordsworth et al., 2011; Selsis et al., 2011; Leconte et al., 2013) and to produce time-dependent maps of narrow band fluxes to generate synthetic observables. To do that, most of the empirical parameterizations (for instance to model the condensation and precipitation) or the detailed properties (like the precise albedos and emissivities associated with the different types of soils, vegetations, ice/snow layers) are no longer used. They are replaced by simplified, but more generic physical laws controlled by a few global parameters (like the radius of the ice/water particles, the soil thermal inertia, emissivity).

This model was applied to the case of present Earth to test its ability to catch the main characteristics of its climate and the associated observables. Although the general properties of Earth climate are reproduced, the simulations produced with this model slightly depart from those obtained with the Earth LMDZ code. In particular the equilibrium and mean surface temperature are lower than that of Earth (or simulated with the Earth LMDZ GCM). This is mainly due to the fact that the radiative effect of ozone is not included (it would require to compute grids of high-resolution absorption coefficients with an additional dimension), which results in a lower forcing. The simplified properties of clouds also yield a lower forcing due to a slightly higher albedo.

We are currently working with recent generic model simulations for the Earth, the aquaplanet Ote–1, and an Earth with a 10 days rotation period (Chapter 5). In this section we present our preliminary results for the mid-infrared spectra and time series obtained for these cases. The analysis of these synthetic observables (from Figure 7.4 to Figure 7.7) will be done after this thesis. However, we can study some main features from the spectral light curves of Figure 7.4 and Figure 7.5. Relating the global brightness temperature of each band to the atmospheric profile, we can identify some atmospheric compounds correspondent to certain bands (named by their center wavelength): water vapor absorption in the low-medium-level of the troposphere (7.14 μm); "atmospheric window", temperature of the low-cloud tops and the surface (11.02 μm), water vapor at the upper levels of the troposphere (40.00 μm), and carbon dioxide at the stratosphere (15.58 μm), the height levels vary in the snowball planet because of the lower lapse rate (Figure 5.11). The curves start at the spring equinox, then for an observer at the northern hemisphere (blue, green) the temperature rises at the surface (11.02 μm) during spring and decreases during autumn. Water vapor bands (7.14 μm, 40.00 μm) have a small seasonal variation because of the accumulation of latent heat associated with evaporation of water at the surface and condensation of water vapor in the troposphere.

7.3 Summary

The use of LMDZ generic GCM spectral data gives the opportunity to reproduce Earth-like planet conditions and simulate the planetary signal detected by a distant observer. By the comparison of the signal received with the Earth spectrum, the type of atmosphere (Figure 7.2) and the abundances of the main atmospheric species, that have spectral features, (Table 7.1) can be identified.

By the calculation of the brightness temperature of each band, a hypothetical atmospheric profile can be traced identifying temperature and height, this calculations allow to determine the surface temperature. By a model of the contribution function of the relative intensity depth between the spectral line and the continuous level, we can determine the depth of the layers of formation of a spectral line, and the results can be compared with the atmospheric profile (Figure 7.3).

The global parameters of the climate can be calculated by the integration to all the thermal range. The effective temperature of the planet correspond to the "bolometric" brightness temperature, the Bond albedo of the planet is retrieved by the application of the energy balance relation (Equation 2.9), assuming the radius of the planet can be measured independently, and the greenhouse parameter is finally given by Equation 2.10 (or Equation 2.12 for g_N).

Unlike spectra, light curves allow to study the time variability of each band and of its atmospheric constituents. The comparative analysis of the autocorrelation series of each band will give the rotation rate of the planet and/or the rotation rate of large weather systems (Section 6.3.3) as in the case of water worlds. Longitudinal curves illustrate the distribution, state and evolution of the various components of the atmosphere, notably biosignatures as H_2O, CO_2, and O_3. Finally, by the typification of a possible next generation telescope (spectral resolution, diameter, technique, S/N, etc...) we can simulate a complete observation. However, because the thermal emission spectrum depends both on the temperature profile and abundances of the infrared absorbents, the results might have degeneracies. Light curves are a promising way to identify them (von Paris et al., 2013).

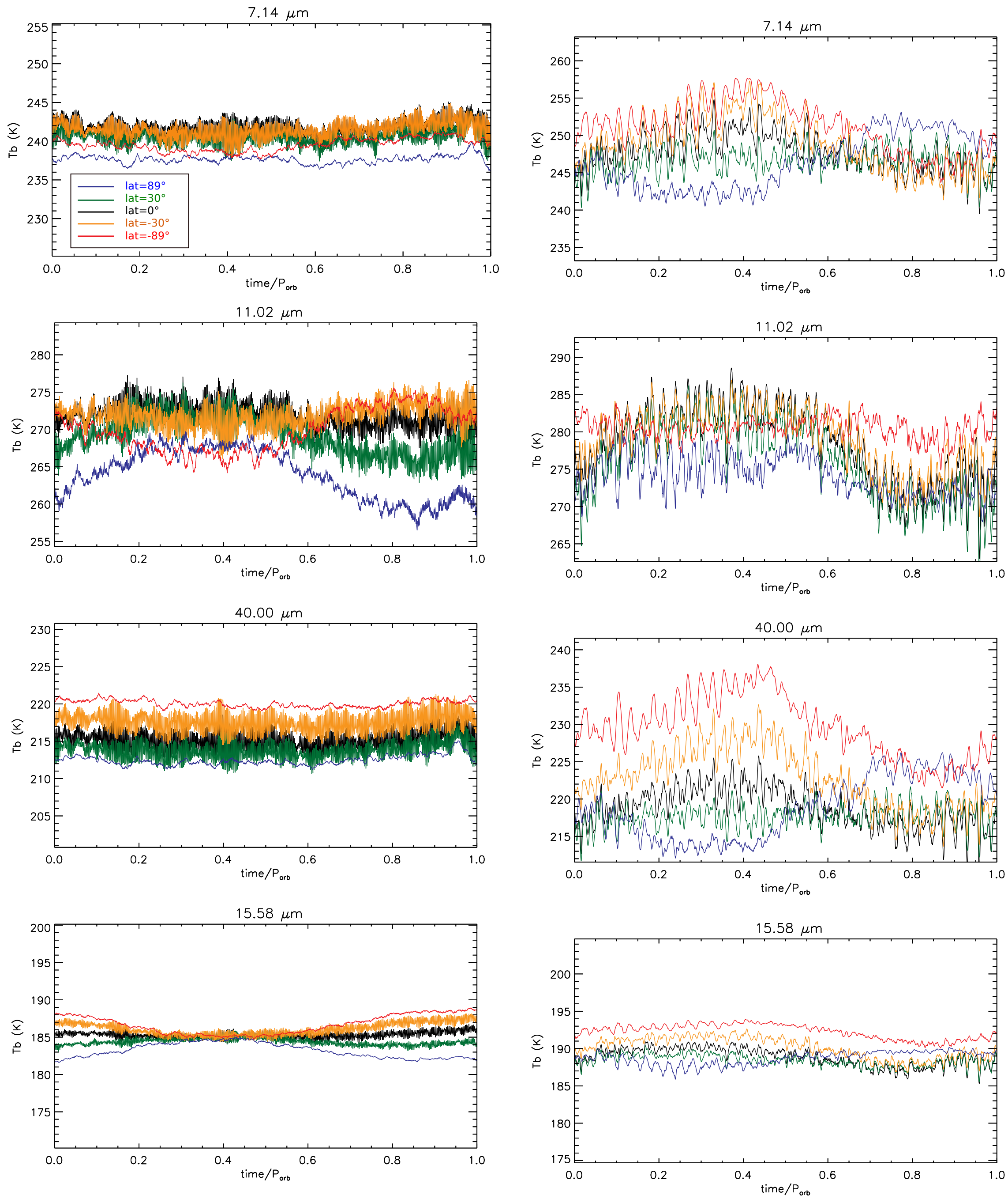

Figure 7.4 TOA-all-sky spectral brightness temperature annual series towards observers at 89N° (blue), 30N° (green), 0° (black), 30S° (orange), 89S° (red), for the planets Ete–1 (left) and Ete–10 (right), the rows correspond to the spectral bands of 7.14μm, 11.02μm, 40.00μm, and 15.58μm, described in Chapter 2.

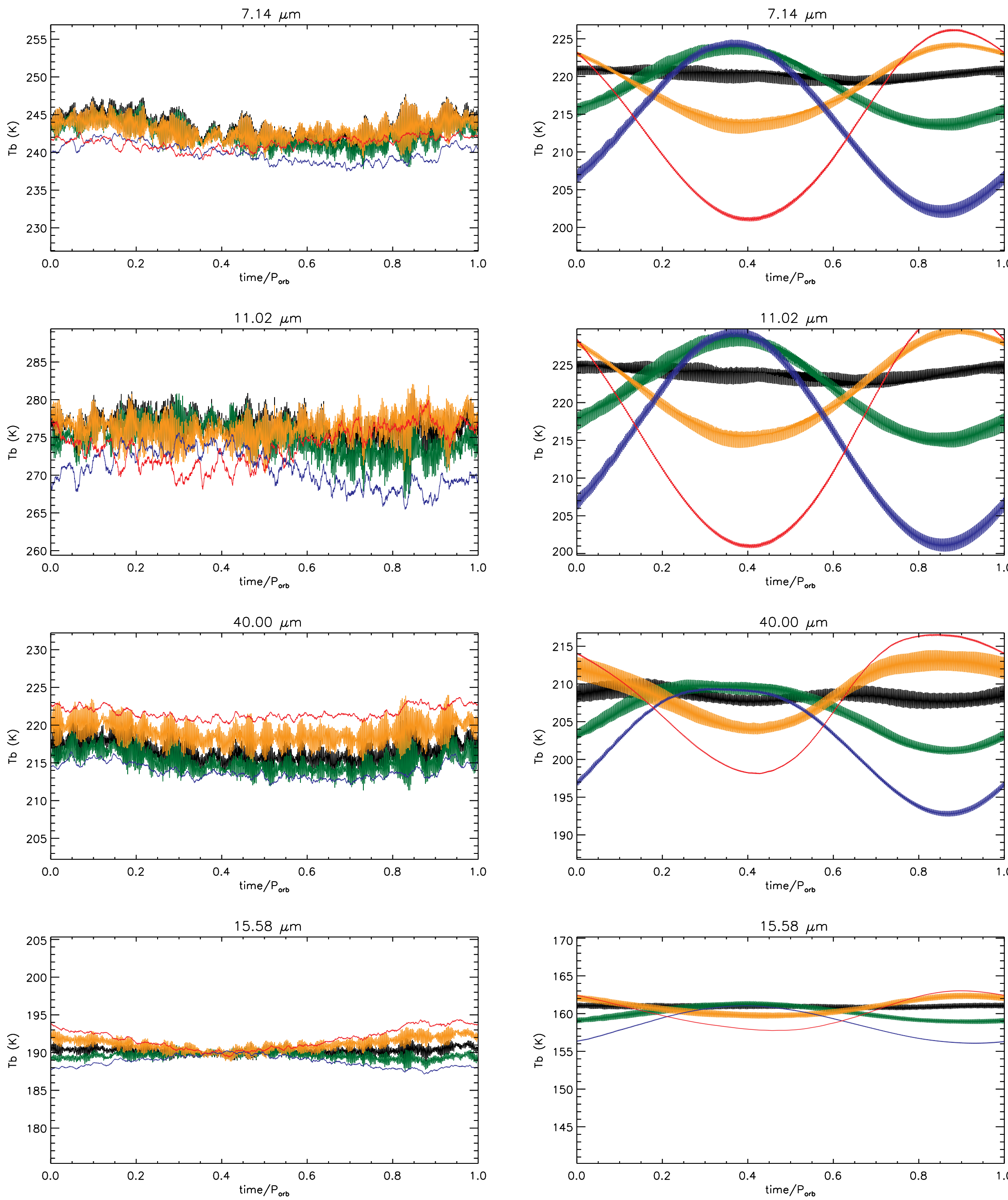

FIGURE 7.5 TOA-all-sky spectral brightness temperature annual series towards observers at 89N° (blue), 30N° (green), 0° (black), 30S° (orange), 89S° (red), for the planets Ote–1 (left) and SOte–1 (right), the rows correspond to the spectral bands of 7.14μm, 11.02μm, 40.00μm, and 15.58μm, described in Chapter 2.

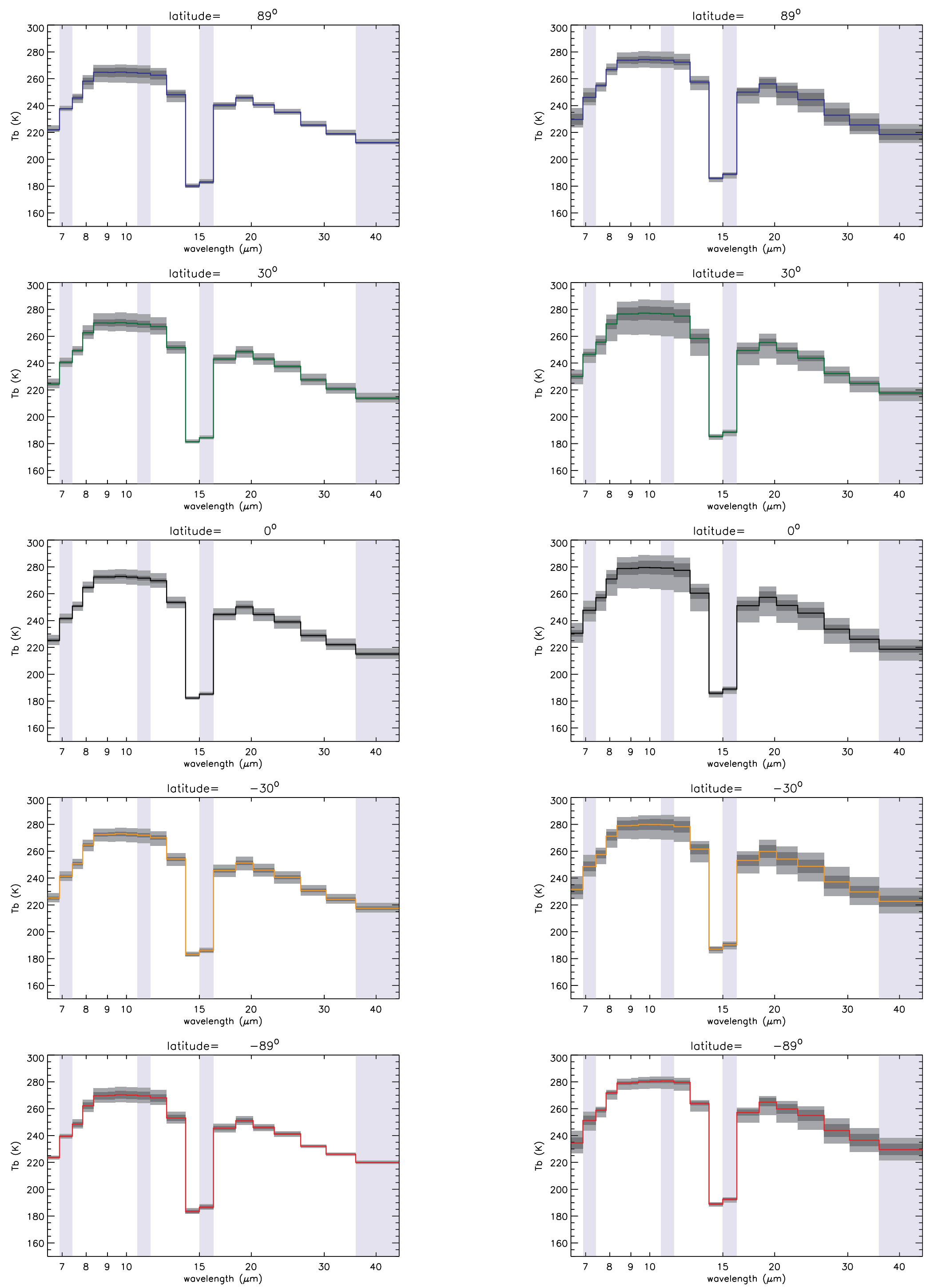

FIGURE 7.6 TOA-all-sky spectra towards observers at (from top to bottom) 89°N, 30°N, 0°, 30°S, and 89°S, for the planets Ete–1 (left) and Ete–10 (right).

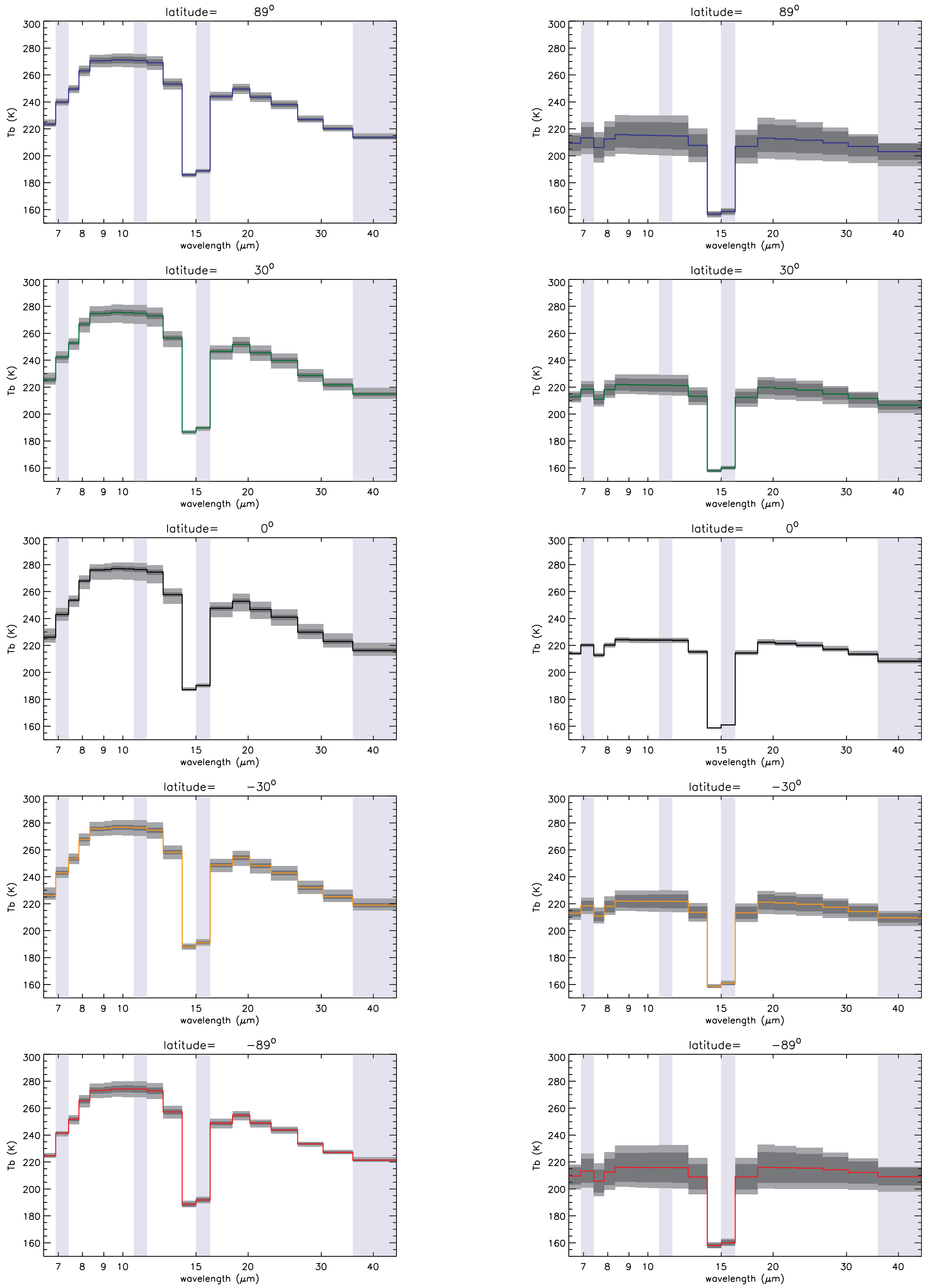

FIGURE 7.7 TOA-all-sky spectra towards observers at (from top to bottom) 89°N, 30°N, 0°, 30°S, and 89°S, for the planets O–1 (left) and SOte–1 (right).

Chapter 8

Conclusions

The study of the Earth-like planets is important to prepare the incoming detection and characterization of extrasolar habitable worlds. The use of climate models gives us the opportunity to built a variety of planets, by changing the planetary properties and simulating any geometry of observation, which it is important to understand their influence on the observables. In this thesis, we have used satellite and model results to simulate thermal light-curves of the Earth and several Earth-like planets, studying the climate and the circulation of the atmosphere and deriving some planetary properties from the spectro-photometric signal, such as the planetary rotation rate, the global temperature of the planet, the existence of seasons, the eccentricity of the orbit, weather patterns or the presence of moons.

8.1 Methods

– I have built a geometrical model that can simulate the point-like emission signal of an Earth-like planet received by an observer at any geometry and distance.

– By the comparison of mean limb darkening models and for the sake of simplicity we conclude that the Lambertian approximation is applicable on the simulation of the thermal emission of the Earth-like planets of our set.

– Our model can also calculate the global characteristics of the planet as the effective temperature, the Bond albedo, the greenhouse parameter, or the cloud radiative forcing to study the climate and to analyze the influence of the variation of these parameters on the signal.

– In addition, by the further analysis of the light curves, we can retrieve certain parameters such as the rotation rate, the albedo and the effective temperature. We can also built longitudinal maps to reveal warm and cold regions of the planet and include the effect of natural satellites.

8.2 Types of data

– Three types of data have been implemented by our model in order to obtain the planetary integrated mid-infrared emission in the direction of a remote observer randomly located.

– First I have used satellite validated data from NASA-SRB project in order to obtain an accurate reproduction of the thermal light curve of the Earth (Chapter 4).

– Secondly, I have used the Earth LMDZ GCM to reproduce the Earth and the results obtained are validated by the comparison with SRB data.

– Then, I have modeled nine Earth-like planets including: a slow Earth, an aquaplanet and a snowball planet with the orbital parameters of the Earth (Chapter 5), two aquaplanets with circular orbits and three synchronous aquaplanets (Chapter 6).

– The use of LMDZ generic model allows the application of data from narrow spectral bands which allows to study of the temporal evolution of the planetary spectrum, and also the distribution, abundances and evolution of its atmospheric components (Chapter 7).

8.3 Photometric variability of the Earth

– I have constructed a 3 hr resolution model of the integrated mid-infrared emission of the Earth over 20 years in the direction of a remote observer randomly located.

– The seasonal modulation dominates the variation of the signal. As expected, it is larger for the polar views because the planetary obliquity causes a bigger annual insolation change for these latitudes. For equatorial views, the seasonal maximum occurs during the summer of the Northern Hemisphere, as the latter contains large continental masses whereas the Southern Hemisphere is dominated by the oceans.

– The rotational variability is detectable because of the uneven distribution of oceans and continents with geographical longitude. The daily maximum of the mid-infrared flux is shown when dry large masses of land, such as the Sahara desert, are in the observer's field of view. The daily minimum appears when cloudy humid regions such as the Indonesian area is visible, as iced big zone are confined to the poles.

– In the polar views, the distribution of land does not change with time but the diurnal temperature variation of large continental areas affects the signal, allowing the detection of the rotational period in the North Polar case.

– I find that the rotational variations have an amplitude of several percents, which is comparable to that of the seasonal variations for some latitudes.

– It is important to remark the strong influence of the weather patterns, humidity and clouds are sometimes able to mask the 24 hr rotation period of the signal for several days at a time. However, this effect can be solved by time folding.

– It is important to point out that the Earth does not exhibit a significant modulation associated with phase variation (phase curve). This is because the integrated thermal emission does not generally probe the boundary layer (first km of the atmosphere) where the diurnal cycle takes place.

– If unresolved, the Earth–Moon system would however present a phase variation of Lunar origin. A satellite of the size of the Moon would introduce a strong phase variability that would completely dominate over the planet's signal. This effect adds high complexity to its interpretation by photometry.

– At the light of these results it seems that future infrared photometric observations of terrestrial planets can be useful in order to characterize their atmospheric and surface features. If the planet is not completely covered by clouds, as Venus is, the presence of strong surface inhomogeneities (continents) can be extracted from the daily variations. The orbital variability can also give estimates of the planet effective temperature, the seasonal cycle, the eccentricity its orbit, and the distribution of land at larger scale.

8.4 Photometric variability of Earth-like planets

8.4.1 Planets in a terrestrial orbit

– I have studied the thermal light curves of four Earth-like planets: The Earth; a slow Earth, with a rotation period of 10 days; an aquaplanet with Earth orbital parameters and a snowball version of this aquaplanet. Climate is highly dependent on surface temperature, Bond albedo, rotation rate, cloud covering and continental distribution. Then, I have calculated the global parameters of the atmosphere, discuss the climatic conditions, and study the influence of the physical characteristics of the planet on the signal.

– In comparison with Earth's climate, a slow Earth has a colder climate, zonal winds are very slow and the meridional circulation dominates, it also has a diurnal convection cloud formation cycle in the form of huge monsoons and a thick layer of low clouds over the oceans. As a result of a large part of the surface is frozen. Unlike the Earth, there are equatorial superrotating winds in the upper levels of the troposphere.

– An aquaplanet analogue has a warmer climate, the greenhouse effect is severe because of the large fraction of high clouds. Surface temperatures of aquaplanets are influenced by the eccentricity of the orbit (the southern summer is warmer because at that moment the planet passes by the periastron).

– The snowball climate is cold and dry with very slow winds, a layer of low cloud covers the surface except in summer, when convection clouds are formed.

– The time series variability of Earth-like planets is produced by three main factors: the seasonality, by which the energy absorbed (and emitted) changes along the orbit because of the inclination of the rotation axis; the rotation of the planet, as the change in flux is created by the contrast between warm and cold areas of successive planetary views; and the diurnal variability, when the temperature cycle of a particular region produces a change in the emission.

– The rotation period of the signal can be retrieved, with a compromise of the length of the time series considered, if cloud lifetimes are longer than the rotation period or if the planet has cloud-convection regions, where clouds are formed constantly. In this case, the regions are characterized for the low brightness temperature from the top of the clouds. The large humidity ratio associated with convection regions is the origin of the periodical signal.

– Finally, I have obtain the longitudinal curves of the planets, which allow us to identify warm and cold regions and the influence of the axial tilt (seasons) and eccentricity of the orbit.

8.4.2 Water Worlds

– I have studied the thermal emission of five aquaplanets with circular orbits and without axial tilt (without seasons): O–1 and O–10 have a rotation rate of 1 and 10 days, respectively; and three synchronous aquaplanets Os–1, Os–10, Os–360 with rotation rates of 1, 10 and 360 days, where the stellar constant is modified according to the orbital distance.

– Aquaplanets analogues are warmer than terrestrial planets, with an ITCZ with a high concentration of convective clouds because the large specific humidity. An aquaplanet with the same orbital parameters than the Earth has an effective temperature of 258 K, an aquaplanet analogue with a circular orbit and without axial tilt, has an effective temperature of 257 K. Synchronous aquaplanets however have low surface temperatures and the main part of the surface is frozen except for the antistellar region, an Earth analogue with a rotation rate of 1 day, has an effective temperature of 238 K.

– The warmest point is usually shifted by the circulation of the planet and being a convergence region, steady convection clouds cover the area, which has a slight effect over the signal by decreasing the TOA-emission at this point.

– Because of the low thermal inertia of water, the cloud absorption is the only source of flux variability in the signal. Thus, the period is retrieved by autocorrelation if the cloud lifetimes are longer than the period of the planet or if the clouds are linked to convergence regions.

– The period is retrieved in the case of the aquaplanet O–1 because the rotation rate is shorter than the clouds lifetimes. O–10 has a convergence region in the form of a “chevron” pattern, however the region is an atmospheric phenomenon and it is not linked to surface steady features. The period obtained is shorter that the period of rotation of the planetary surface, because the equatorial superrotating winds in the upper troposphere drive the clouds of the “chevron” pattern. The movement of the chevron pattern is shown in longitudinal light curves.

– The period of tidally looked planets is retrieved because the convergence regions are tied to the surface temperature maximum.

8.5 Perspectives

– The use of LMDZ generic GCM spectral data gives the opportunity to reproduce Earth-like planet conditions and simulate the planetary signal detected by a distant observer. By the comparison of the signal received with the Earth spectrum, the type of atmosphere (Figure 7.2) and the abundances of the main atmospheric species, that have spectral features, (Table 7.1) can be identified.

– By the calculation of the brightness temperature of each band, a hypothetical atmospheric profile can be traced identifying temperature and height, this calculations allow to determine the surface temperature. By a model of the contribution function of the relative intensity depth between the spectral line and the continuous level, we can determine the depth of the layers of formation of a spectral line, and the results can be compared with the atmospheric profile (Figure 7.3).

– The global parameters of the climate can be calculated by the integration to all the thermal range. The effective temperature of the planet correspond to the ”bolometric” brightness temperature, the Bond albedo of the planet is retrieved by the application of the energy balance relation (Equation 2.9), assuming the radius of the planet can be measured independently, and the greenhouse parameter is finally given by Equation 2.10 (or Equation 2.12 for g_N).

– Unlike spectra, light curves allow to study the time variability of each band and of its atmospheric constituents. The comparative analysis of the autocorrelation series of each band will give the rotation rate of the planet and/or the rotation rate of large weather systems (Section 6.3.3) as in the case of water worlds. Longitudinal curves illustrate the distribution, state and evolution of the various components of the atmosphere, notably biosignatures as H_2O, CO_2, and O_3. Finally, by the typification of a possible next generation telescope (spectral resolution, diameter, technique, S/N, etc...) we can simulate a complete observation. However, because the thermal emission spectrum depends both on the temperature profile and abundances of the infrared absorbents, the results might have degeneracies. Light curves are a promising way to identify them (von Paris et al., 2013).

– The topic of this thesis was the study of the thermal emission of Earth-like planets. Although the observation of these type of planets will be possible in a decade, this model is also applicable to the study of other types of planets. The next step is to implement the model with the purpose of Super-Earths, as this type of planets are detectable nowadays.

Chapter 9

Conclusions (français)

Les conclusions finales de cette thèse sont présentées comme un résumé des conclusions indiquées dans chaque chapitre. L'étude des planètes telluriques est important pour préparer la détection et la caractérisation futures des planètes extrasolaires habitables. L'utilisation de modèles climatiques nous donne la possibilité de construire une grande variété de planètes, en modifiant les propriétés planétaires et de simuler n'importe quelle géométrie de l'observation, ce qui est important pour pouvoir comprendre leur influence sur les observables. Dans cette thèse, j'ai utilisé des donnés satellitaires et des donnés des modèles climatiques pour simuler l'emission thermique et les courbes de lumière de la Terre et de plusieurs planètes telluriques. L'analyse de nos résultats permet de étudier le climat, la circulation de l'atmosphère et de dériver des propriétés planétaires à partir du signal spectro-photométrique, comme le taux de rotation planétaire, la température globale de la planète, l'existence des saisons, l'excentricité de l'orbite, les conditions météorologiques ou la présence des satellites naturels.

9.1 Méthodes

– J'ai construit un modèle géométrique qui permet de simuler le signal de l'émission ponctuelle d'une exoplanète tellurique reçu par un observateur à toute géométrie et distance.

– Par la comparaison des modèles de la moyenne du “limb-darkening” terrestre