論文の内容の要旨

論文題目： Exploring the Landscape of Habitable Exoplanets via Their Disk-integrated Colors and Spectra: Indications for Future Direct Imaging Observations

(惑星光による系外地球型惑星の表層環境の推定：将来の直接撮像観測にむけて)

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Discoveries of extrasolar planets (exoplanets) have drastically changed and still continue to change our views of the universe. In particular, recent surveys of exoplanets suggest the presence of numerous Earth-size / super-Earth-size planets in the so-called habitable zones (HZs). This inspires us to seriously address one of the most fundamental questions in science, the existence of planets harboring life outside the Solar System. In order to answer the question, both theoretical and observational investigations remain to be done. A reasonably realistic possibility towards the goal is to search for any biological signatures in the photometric and spectroscopic data with direct detection of the planetary light separated from the host star. Currently, several proposals for direct imaging of rocky planets in HZs are under active discussion.

In order to consider the feasibility for such future observations, the disk-integrated spectra of the Earth and Earth analogs have been studied via numerical simulations and observations. The scattered light in principle carries information of the planetary surface through the reflection properties of various components. Indeed, the colors of the Earth in the visible-NIR range exhibit diurnal variation depending on the nature of the surface components in the illuminating region, as first pointed out by Ford et al. (2001). Interestingly, vegetation on the Earth has peculiar reflection spectra in this range, a rapid increase in reflectivity at $\lambda \sim 0.8$um (known as the red edge); this feature is recognized as one of the potential "biomarkers". Spectral features of the Earth include the absorption bands of atmospheric molecules, some of which are associated with bioactivity. Oxygen, for instance, is considered as an important biomarker because oxygen on the Earth has mainly originated from biological activity.

While a number of simulations of the disk-integrated scattered light of the Earth have been presented previously, the inversion of the data is not straightforward due to the complexity of the scattering processes taking place in planetary surface layers. In particular, inhomogeneous cloud cover and the diversity of surface components make it hard to recover the detailed information of the surfaces.

In this thesis, we study the scattered light of the Earth and Earth analogs using the observed data of the Earth and relevant simulations, with particular emphasis on the possibility of reconstructing the surface features of exoplanets. We focus on the *time variabilities* of the planetary colors and spectra due to the planetary spin rotation and/or orbital motion that enable us to probe the inhomogeneity of the planetary surface and to capture the localized features.

The main part of this thesis is organized as follows. Chapter 3 explains our simulation scheme and compares the results with the multi-band photometry of the Earth by NASA's EPOXI spacecraft. Chapter 4 discusses the inversion of the observed data to recover the longitudinal surface map. Chapter 5 explores the possibility of 2-dimensional mapping of exoplanets from yearly light curves. Chapter 6 studies the variability of absorption features imprinted in the disk-integrated spectra of the Earth and discusses its potential to probe the water cycle. Chapter 7 examines the feasibility of the methods described in Chapters 4, 5 and 6, with future space-based missions in mind. Finally Chapter 8 draws our main conclusion. The contents of the main chapters are summarized below.

In Chapter 3, we consider the multi-band photometric data (color) of the Earth at λ=0.3-1.0um obtained with EPOXI. We present a simulation scheme incorporating the elaborate radiative transfer calculation in the atmosphere and the diversity of the surface, and confirm that the scheme can reproduce the observed data well. While the time-averaged colors of the present Earth is close to that of typical clouds, the diurnal trajectories in a color-color plot show occasional deviations toward the colors of ocean, land and even vegetation, suggesting a possibility of identifying those surface components separately from clouds.

Then, in Chapter 4, we analyze the observed multi-band photometric data with a simple inversion model adopting the representative surface components: clouds, ocean, soil, vegetation and fine snow. Despite the rather crude assumption adopted in our inversion model, major features such as the Sahara desert and the Pacific/Atlantic oceans and even the distribution of vegetation are recovered if good signal-to-noise ratios of the reflection spectra are achieved; we take account of the observational noise and the model dependence, and find that ocean and clouds could be inferred with S/N>10-20, while other components are more likely to suffer from the degeneracy among the components. Vegetation is relatively easy to decompose, due to the strong red-edge feature. Our current analysis also indicates that measurements with S/N>20 are needed to distinguish between the observed data and a model with clouds and oceans alone, and hereby to claim the presence of less dominant components other than ocean and clouds.

In Chapter 5, we further develop a technique of the 2-dimentional (latitudinally and longitudinally resolved) mapping of the Earth from yearly light curves by considering not only the planetary spin rotation but also the orbital motion. We develop a regularized inversion method named SOT, which decomposes the total scattered light into the reflectivity at each surface pixel without assuming particular reflection models. In order to demonstrate its feasibility, we create mock yearly light curves of an Earth-twin in 3 photometric bands (0.4-0.5um, 0.6-0.7um, 0.8-0.9um) using our simulation scheme. By applying the SOT to them, we find that the mapping from single-band photometry can detect the snow and/or cloud distribution. Since their reflectivity is roughly independent of wavelengths, we also show that the mapping of the difference between 2 photometric bands reveals the underlying surface features including the continental distribution and the localized vegetation areas. In the inversion procedure, the planetary obliquity is also estimated reasonably well in most cases if the degree of the surface inhomogeneity is similar to, or even larger than, that of our Earth; the obliquity is an important parameter to discuss the planetary climates as well as to constrain the planet formation scenario. The anisotropic scattering by clouds that can potentially cause the bias in fitting can be suppressed by ignoring the data at crescent phases.

In Chapter 6, we examine the variability of atmospheric absorption features imprinted in the NIR disk-integrated spectra of the Earth obtained with EPOXI. There are prominent bands of H_2O, O_2, and CO_2 in there. We find that there are roughly 5-15% of diurnal variations in their equivalent widths. The cross-correlation analysis indicates that the variation should be attributed to the uneven cloud cover. Our simple model under the “opaque cloud” assumption reasonably reproduces the observed variation pattern. We also notice that variation patterns of H_2O and O_2/CO_2

are different, and interpret them due to the non-uniformity of the water vapor in the atmosphere. The spatial and temporal variabilities of atmospheric water vapor result from its short mean residence time due to the large production flux (via e.g. evaporation) compared to the atmospheric abundance. Thus, such an inhomogeneity may suggest a substantial amount of reservoir producing water vapor into the atmosphere, probably liquid water. Therefore, the variability of water vapor absorption bands as well as those of the other well-mixed gases may be a good indicator of the water cycle on the exoplanets in HZs.

Finally, in Chapter 7, we discuss the requirements for future direct imaging instruments and/or observational strategy by estimating the noises coming from the planetary photon itself, the speckle, the zodiacal light, the read-out noise, and the dark current, assuming a CCD-type detector. We assume that the light curve is folded according to the spin rotational period. With an optimistic set of instrumental parameters, reconstruction of surface features from multi-band photometry typically requires a space-based observatory with >4m aperture for an Earth-twin at 10 pc. More precise measurement capable of inferring the presence of the minor components (S/N>100) will be possible only for nearby planetary systems (<5pc) with >10m aperture. Detecting the variability of equivalent widths of molecular absorption features is more demanding. For nearby Earth-twins, typically >6-10m aperture will be required with filters finely tuned for the absorption band detection. The estimate of S/N, however, highly depends on many factors such as the planetary radius and the spectral type of the host star as well as the instrumental set-up.

These new approaches point out a realistic possibility to remotely probe the exoplanetary surfaces and even provide important signatures of habitability that would otherwise be unattainable. Given our current ignorance of life outside the Earth, it is an essential scientific step towards characterization of possible habitats on exoplanets rather than the mere identification of biomarkers; the form of life is intimately related to the surrounding environmental system including the presence of liquid water (ocean), continents, and clouds. Our results expand the horizon towards the landscape of “other worlds” with detailed direct imaging observations and thus strongly motivate such future projects.