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Characterizing exoplanetary atmospheres through infrared polarimetry

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Abstract

We present calculated thermal polarization signals from hot exoplanets, using a doubling-adding radiative transfer model that spatially resolves the disk of the planet, allowing the simulation of horizontally inhomogeneous planets. Our calculations show that the degree of linear polarization, P, of an exoplanet's thermal radiation is expected to be highest near the planet's limb and that this P strongly depends on the temperature and its gradient, and the scattering properties and distribution of the cloud particles. Planets that do not appear to be spherically symmetric, e.g. due to flattening, cloud bands or spots in their atmosphere, differences in their day and night sides, and/or obscuring rings, give P values that are often larger than 0.1%, in favorable cases even reaching several percent at near-infrared wavelengths. Detection of thermal polarization signals can give access to planetary parameters that are otherwise hard to obtain: it immediately confirms the presence of atmospheric clouds, and P can then constrain atmospheric inhomogeneities and the flattening due to the planet's rotation rate. For zonally symmetric planets, the angle of polarization will yield the components of the planet's spin axis normal to the line-of-sight. Our calculations also show that P is generally more sensitive to variability in a cloudy planet's atmosphere than flux is, making polarimetry very suitable for detecting phenomena associated with atmospheric dynamics.

1. Introduction

Stellar light that is reflected by a planetary atmosphere will usually be polarized, due to scattering of clouds and molecules [3] [5]. On the other hand, light being emitted by, for example, a Brown Dwarf can also become polarized when scattering takes place in the atmosphere [2]. For a spatially unresolved object the net degree of linear polarization, P, of the thermal radiation will equal zero when it is horizontally homegeneous. A horizontally inhomogeneous distribution of temperature or clouds, or a non-spherical shape of the object can cause the thermal radiation to have a net polarization signal. For polarized Brown Dwarfs a plausible candidate for the source of polarisation is a flattening of the body due to fast rotation [4]. Here, we calculate signals of horizontally inhomogeneous planets and explore parameters that determine the strength of these thermal polarization signals, and discuss the value of infrared polarimetry for the characterization of exoplanet atmospheres.

2. Spatially resolved polarimetry

We calculate the radiative transfer in a locally plane-parallel, vertically inhomogeneous planetary atmosphere for a range of emission angles using a doubling-adding method [6], which fully includes all orders of scattering and polarization. We first look at how the polarization varies across the planetary disk with varying atmospheric parameters. We assume ad hoc temperature profiles with temperature gradients that are constant with $\ln p$ and a geometrically thin cloud layer, high in the atmosphere, with a given optical depth and Rayleigh scattering particles.

We find that P is largest near the limb of the planet, where singly scattered light from below is scattered at angles close to 90°, which gives the highest polarization for Rayleigh particles. For an atmosphere that has temperatures decreasing with decreasing pressures near its limb, the polarization direction near the limb is parallel to the local horizon. A larger temperature gradient will give rise to a larger P at the limb, as the radiation field near the scattering particles will become more dominated by the hot radiation coming from directly below, before being scattered at angles near 90°. For a negative temperature gradient (temperatures rising with decreasing pressure) multiple scattering is more important, resulting in the polarization direction being orthogonal to the local horizon. Because of the multiple scattering, P is lower for temperature profiles with negative gradients than for positive ones.

Increasing cloud optical thickness for a positive temperature gradient will at first increase P near the limb, but will decrease again when the optical thickness becomes larger than $\sim$0.1, as multiple scattering starts playing a larger role. Lowering the cloud layer will not change P much until the gas absorption optical thickness will be similar to the cloud optical thickness, when P will vanish as absorption starts dominating. When the cloud is at the top of the atmosphere, P will be largest in gas absorption bands, whereas if the cloud is at altitudes where gas absortion is significant, P will be lowest in absorption bands.

3. Disk-integrated polarimetry

We define a latitude-longitude grid of $2^\circ \times 2^\circ$, calculate the polarization signals across the disk, and integrate them over the disk. Horizontally homogeneous spherical planets indeed yield a net P of zero. For a horizontally homogeneous ellipsoidal planet and a temperature slope of 300 K/$\ln p$, we get a similar values of P as a function of oblateness as [4] for their models with $T_{\rm eff}$ =1800 K and $\log g = 4.5$. We also calculated P for planets with a banded structure and for planets with obscuring rings under a wide range of viewing geometries. The net P is often larger than 0.1%, in several cases reaching several percent. The above three cases all have a zonal symmetry, which means that the axis of symmetry is alligned with the spin axis of the planet. In these cases, the direction of polarization is either parallel or orthogonal to the spin axis of the planet. Calculations of a dusty hot spot rotating into view, as well as calculations of planets with a day-night temperature and dust difference show that P and the direction of polarization vary more strongly than the infrared flux.

4. Summary and Discussion

Our calculations show that the infrared radiation emitted by exoplanets can be polarized by several percent and that the polarization is sensitive to the temperature, the temperature gradient, the cloud particle properties, cloud height and the cloud optical thickness. These high values of P can occur both for ellipsoidal planets (like for Brown Dwarfs [4]) and horizontally inhomogeneous planets. A detection of an infrared polarized signal will immediately confirm the presence of scattering particles, such as cloud particles, in the planetary atmosphere. In addition, the polarization direction will reveal the components of the planet's spin axis normal to the line-of-sight for zonally symmetric planets. For such planets, both P and the intensity will show little variability. On the other hand, if the polarization is caused by transiting clouds or hot spots, both P and the polarization direction will vary in time, and stronger than flux. Hence, a time series of polarization measurements will give insight into dynamical processes, and a periodic signal could even yield atmospheric rotation rates.

There are several reasons why planets like those in the HR 8799 system might be more prone to producing polarized signals than Brown Dwarfs, which have been shown to be polarized by up to a few percent. Firstly, the surface gravity of planets is lower than that of Brown Dwarfs, making them more flattened for a given rotation rate. Secondly, broadband flux measurements suggest the HR 8799 planets to be more cloudy than Brown Dwarfs, which might be common to young planets [1]. Thirdly, the effective temperatures in the planets' atmospheres are lower than those in known polarized Brown Dwarfs and, given a certain temperature gradient, lower temperatures will yield higher values of P.

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