The Phase-Dependent Infra-Red Brightness of the Extrasolar Planet υ Andromeda b

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The star υ Andromeda is orbited by three known planets (*1*), the innermost of which has an orbital period of 4.617 days and a mass at least 0.69 that of Jupiter. This planet is close enough to its host star that the radiation it absorbs overwhelms its internal heat losses. Here we present the 24-μm light curve of this system, obtained with the Spitzer Space Telescope. It shows a clear

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variation in phase with the orbital motion of the innermost planet. This is the first demonstration that such planets possess distinct hot substellar (day) and cold antistellar (night) faces.

Last year, two independent groups (*4, 5*) reported the first measurements of the infrared light emitted by extrasolar planets orbiting close to their parent stars. These 'hot Jupiter' (*3*) planets have small enough orbits that the energy they absorb from their hosts dominates their own internal energy losses. How they absorb and reradiate this energy is fundamental to understanding the behavior of their atmospheres. One way to address this question is to monitor the emitted flux over the course of an orbit, to see whether the heat is distributed asymmetrically about the surface of the planet.

We have observed the υ Andromeda system with the 24-μm channel of the Multiband Imaging Photometer for Spitzer (MIPS) (*6*) aboard the Spitzer Space Telescope (*7*). We took 168 three-second images at each of five epochs spread over 4.46 days (97% of the 4.617-day orbital period of υ Andromeda b) beginning on 18 February 2006 at 12:52 UTC (Coordinated Universal Time). After rejecting frames with bad pixels near the star and those with Spitzer's 'first frame effect' (*4*) (2% − 8% of the data, depending on epoch), we measure the flux of the system and that of the surrounding sky using both sub-pixel, interpolated aperture photometry and optimal photometry (*8, 9*) on each frame.

The detection of eclipses (*10*) from the "hot Jupiter" planetary systems HD 209458b (*4*), TrES-1 (*5*) and HD 189733b (*11*) demonstrate that a small fraction ($\sim 0.1\%$) of the total infrared light we observe from these systems is actually emitted from the planet rather than the star. Thus, if we can measure the flux of a system at a signal-to-noise ratio (S/N) > 1000, temperature differences between the day and night faces of the planet will appear as an orbital modulation of the total system flux. With a star as bright as υ Andromeda, our three-second exposures each have S/N ~ 500, so that our SNR expectation is $\sim \sqrt{160} \times 500 \approx 6300$ at each epoch.

The MIPS instrument acquires data by placing the stellar image in a sequence of 14 positions on the detector. The detector's response varies with position at the $\sim 1\%$ level. This variation is stable and reproducible, so we calculate correction factors as follows: At each epoch we compute the mean measured system flux at each position and take the ratio with the mean in the first position. We then average this ratio over all epochs for each position. This results in corrections $< 2\%$ between positions, with uncertainties $\sim 6 \times 10^{-4}$. Bringing the photometry to a common normalization allows us to average over all the frames in each epoch to achieve S/N ≈ 4350 at each epoch.

As with most infrared instruments, MIPS's sensitivity varies in time. We correct for such drifts by dividing the system flux value by the measured background in each frame. The background at 24 μm is thermal emission from the zodiacal dust. This dust pervades the inner solar system, absorbing light from the sun and reradiating it at infrared wavelengths. At 24 μm, its emission is strong enough for use as a flux standard, a technique used successfully in measuring the eclipse of HD 209458b (*4*). However, the present work requires one additional correction. The zodiacal background is the integrated emission by dust along the line of sight between the

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telescope and the object. The observed value thus undergoes an annual modulation as that line of sight varies with the telescope's orbit about the sun. The best available model (*12*) predicts a linear drift over the brief interval of our observations. However, we cannot use the Spitzer model directly, since it is calculated for a line of sight from the Earth to the object in question. The difference in position between the Earth-trailing telescope and the Earth itself is large enough that the slope of the variation may be slightly different. Thus, we fit for the linear drift directly, simultaneously with any model lightcurve fits.

The phase curve for the υ Andromeda system shows a variation (Fig 1) in absolute photometry, even before any corrections for instrumental or zodiacal drifts are made. After the calibration with respect to the zodiacal background is applied, this variation is revealed to be in phase with the known orbit of the innermost planet of the system, our principal result.

A simple model can be fit to the phase curve (Fig 2), assuming local, instantaneous thermal reradiation of the absorbed stellar flux. In the simplest model, the phase of the variation is not a free parameter, but is rather set by the measured radial velocity curve (*2*). Phase offsets are possible for models in which the energy is absorbed deep within the atmosphere and redistributed about the surface (*13, 14*). There is weak (2.5σ) evidence for a small phase offset in this data (Fig 2) but the large offsets predicted from some models are excluded at high significance. Fitting the peak-to-trough amplitude to the observations yields a best-fit value for the planet-star flux ratio $2.9 \pm 0.7 \times 10^{-3}$ times the star's brightness. This is very similar to the result at this wavelength for HD 209458b (*4*). However, the latter is a measure of the absolute flux from the planet divided by that from the host star, while the present result is a measure of the flux difference between the projected day and night sides, divided by the flux of the (different) host star.

Another difference between the cases of υ Andromeda b and HD 209458b is that we do not have a strong constraint on the orbital inclination in this system, so we must include the unknown inclination in the model fit (Fig 3). At higher inclinations, parts of both the night side and the day side are always visible, so the true contrast between the day and night sides must be larger than the amplitude of the observed variation. This contrast is ultimately driven by the light absorbed from the star, which therefore provides an upper limit. We know the distance of the planet from the star and the stellar properties, so we can estimate the contrast that would result if all of the observed flux were reradiated from the day side and nothing from the night side. If we assume the planet's radius is <1.4 Jupiter radii (as observed for other planets of this class), then we can constrain the expected amplitude to be $< 3.4 \times 10^{-3}$ (2σ) for a simple blackbody, no-redistribution model with zero albedo. Thus, a consistent picture of the atmospheric energetics emerges as long as the orbital inclination is $>30°$.

A natural question to ask is whether there are any plausible alternative models for the observed variation. The estimated rotation period of the star is too long to explain our phase curve as the result of a normal starspot (which is darker than other parts of the stellar surface). One could posit a feature on the stellar surface similar to a starspot but induced by a magnetic interaction between the star and the planet, and therefore moving synchronously with the planet. However, (*15*) place an upper limit of 1.6×10^{-4} on the amplitude of optical variation with the

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planetary orbital period, so infrared variability from the star should be even weaker than this. Some evidence for such magnetospheric interactions is found in observations of chromospheric calcium H and K lines (*16*) and has even been seen in the υ Andromeda system. However, the energy input needed to explain the Ca lines is $\sim 10^{27}\mathrm{ergs\,s^{-1}}$, much less than the minimum planetary luminosity we infer here ($\sim 4 \times 10^{29}\mathrm{ergs\,s^{-1}}$). Indeed, one can make a quite general argument that our observations cannot be powered by the same mechanism, since any heating of the star due to magnetic interaction with the planet ultimately extracts energy from the planetary orbit. Thus, one may calculate an orbital decay time

$$\tau = \frac{GM_*M_p}{2a\dot{E}} = 5 \times 10^6 \mathrm{yr} \left(\frac{M_p}{M_J}\right) \left(\frac{a}{12R_\odot}\right)^{-1} \left(\frac{\dot{E}}{10^{30}\mathrm{ergs\,s^{-1}}}\right)^{-1},$$

where M_* and M_p are the stellar and planetary masses, a is the semi-major axis and $\dot{E}$ is the observed heating rate. Heating at the level necessary to explain our observations would result in the decay of the planetary orbit on timescales $<10^7$ years, while the estimated age of the system is 3 Gyr. As such, the chromospheric heating of the star is unlikely to be related to the effect seen at 24 μm.

This observation reveals the presence of a temperature asymmetry on the surface of an extrasolar planet. The first measurements of eclipses (*4,5*) yielded measurements of the absolute flux levels emerging from the day sides of two extrasolar planets. When compared with models of radiative transfer in such atmospheres (*17, 18, 19, 20*), those observations are consistent with a situation intermediate between no redistribution and full redistribution. A similar comparison is possible in this case (Fig 4). Our observed day-night flux difference is comparable to the flux emerging at full phase in the models of (*17*), which indicates that there is little evidence for redistribution of energy to the night side.

In conclusion, the observation of the phase curve of υ Andromeda b indicates that significant temperature differences exist between the day and night faces of the planet, consistent with a model in which very little horizontal energy transport occurs in the planetary atmosphere. Furthermore, it indicates that the opportunities for direct extrasolar planetary observations are better than previously thought, since useful data can be obtained even in cases where the planetary orbit is not so fortuitously aligned that the system exhibits transits or eclipses.

References and Notes

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3. There is no official terminology for planets that orbit close to their parent stars. The term "Hot Jupiter" is the most common, although some authors have adopted other terms, such as "Pegasids","Pegasi planets", or "Roasters".

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10. The passage of an extrasolar planet behind its star — an eclipse — results in a drop in the total system flux. This allows a measurement of the absolute flux emerging from the part of the planet that faces the star (the day side). This is possible when the orbit is aligned almost edge-on to the line of sight.

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12. We use the estimator provided by the Spitzer Science Center, which is based on the DIRBE model described by (*22*). Further information on the specific implementation is given at `http://ssc.Spitzer.caltech.edu/documents/background`.

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23. The usual estimate given for planetary temperatures is equilibrium temperature T_{eq}, defined as the effective temperature of a uniformly bright planet radiating energy at a rate that balances the irradiation received from the star. T_{eq} is thus determined by the stellar effective temperature T_{eff}, stellar radius R and distance of the planet from the star a; $T_{\mathrm{eq}} = 1840\ \mathrm{K}(T_{\mathrm{eff}}/6212\ \mathrm{K})(R/1.57 R_{\odot})^{1/2}(a/0.059 \mathrm{AU})^{-1/2}$, in the case of υ And b with zero albedo. However, in a proper no-redistribution model, the temperature distribution is not uniform but rather hottest at the substellar point and coolest at the limb, and the full-phase temperature average over the planetary surface is better approximated by $(4/3)^{1/4}T_{\mathrm{eq}}$. This is the temperature we adopt, which is 1977 K in this case.
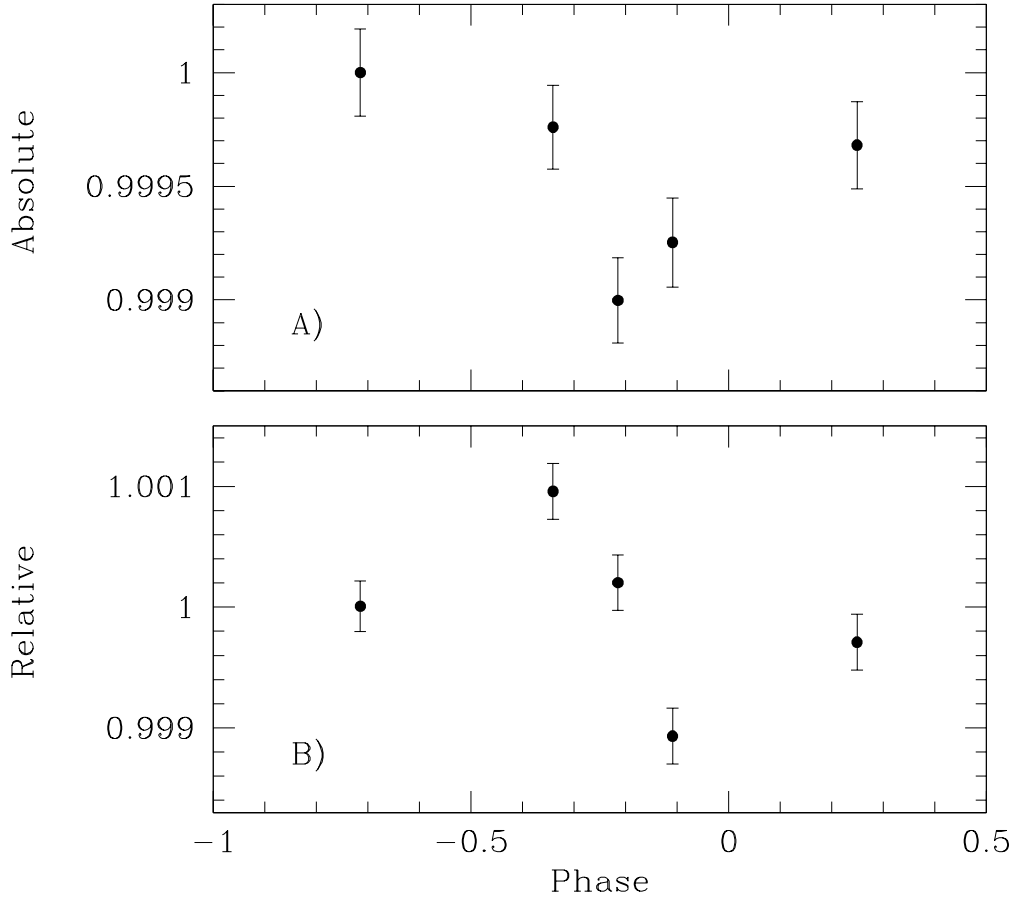
Figure 1: The light curve of the υ Andromeda system. A) The phase variation in the υ Andromeda system flux before any corrections are applied for instrument or zodiacal drifts. Variations in the system flux are significant even at this point. B) By comparing to the zodiacal background, and fitting for the linear drift in the background due to the telescope's motion, we obtain the phase curve shown. In each case, phase is shown modulo unity, with zero phase occurring when the planet is closest to earth. The amplitude units are expressed in terms of the system flux at the first epoch.
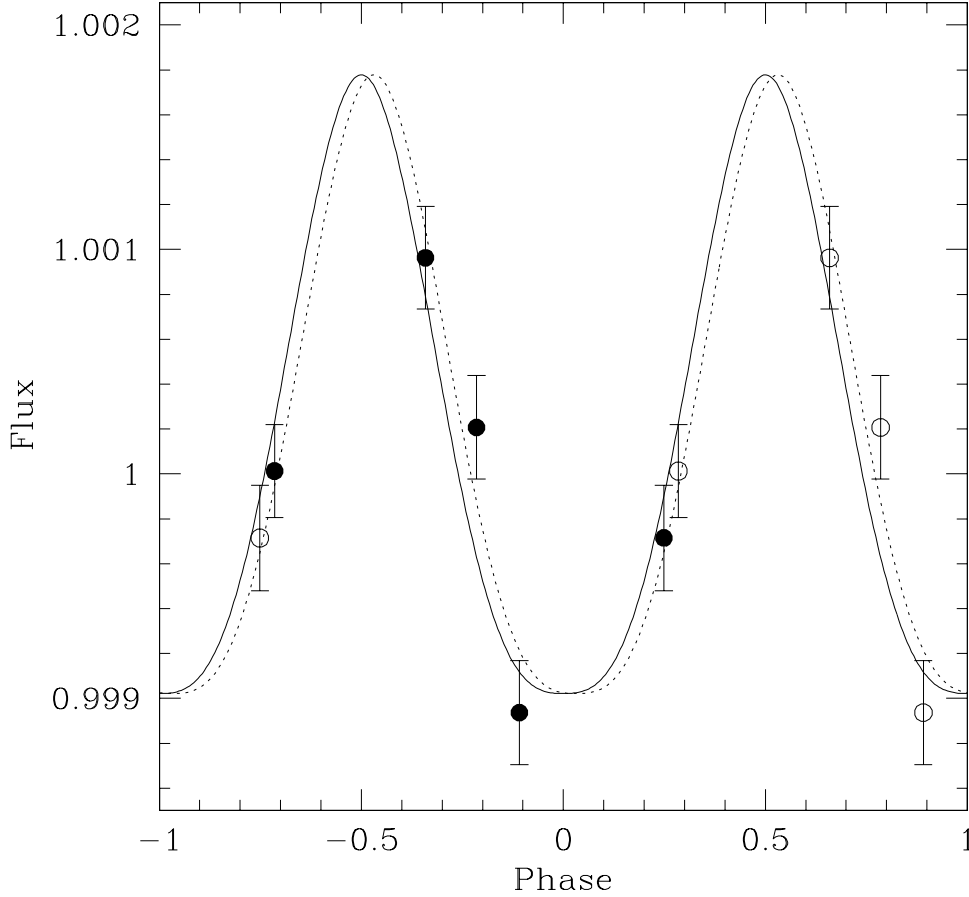
Figure 2: Comparison of the phase curve and the No-Redistribution Model. The solid points show our final phase curve, after applying calibrations, in time order from left to right. The open points are repetitions of these, displaced horizontally by one orbit, to better illustrate the phase coverage over two cycles. The solid line is an analytic model for the planetary emission in which energy absorbed from the star is reradiated locally on the day side with no heat transfer across the surface of the planet, the so-called No-Redistribution model (and in excellent agreement with the more detailed version in (*18*)). The assumed inclination in this case is 80° from pole-on, and the relative planet/star amplitude is 2.9×10^{-3}. If we allow for a phase shift relative to the radial velocity curve, we obtain a slightly better fit, as shown by the dotted curve. The best fit is obtained with a phase lag of 11°, but zero lag is excluded only at the 2.5σ level.
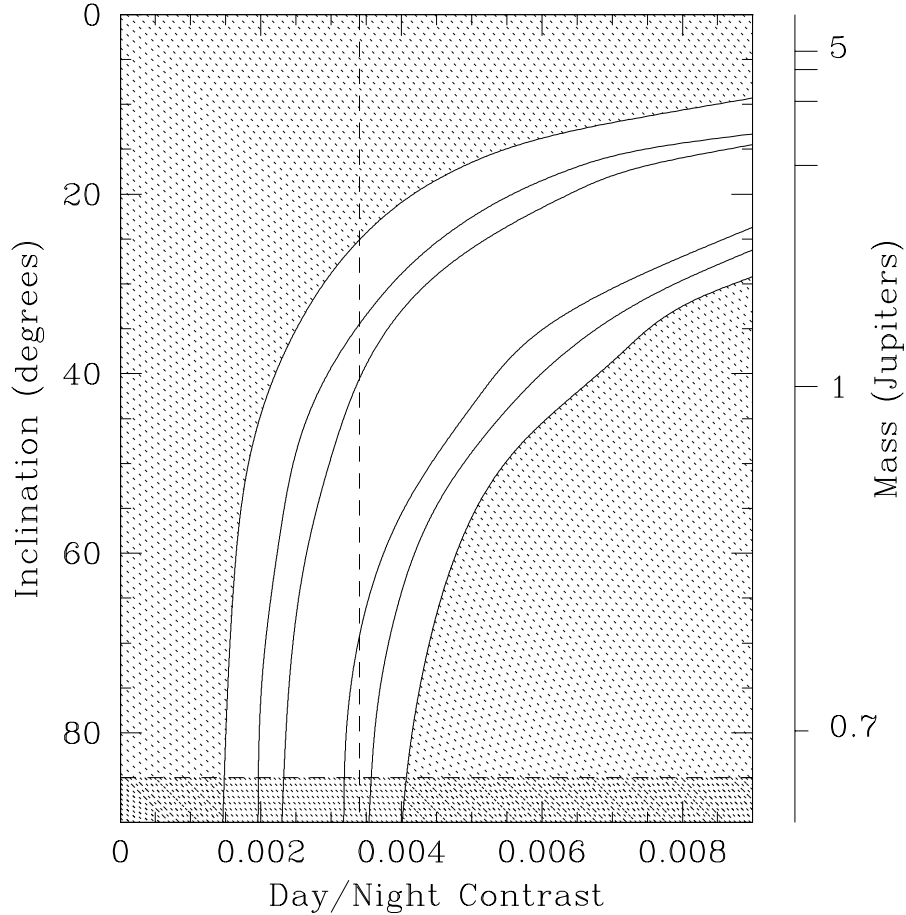
Figure 3: The influence of inclination on the inferred Day-Night contrast. The solid contours bound the $1, 2$ and 3σ confidence regions for the day-night flux difference (in units of the stellar flux), determined as a function of assumed orbital inclination (measured relative to a face-on orbit). The large shaded regions indicate those values excluded at $3\,\sigma$. The lower shaded region is excluded because the planet does not transit in front of the star. The vertical dashed line indicates the expected upper limit to the contrast, obtained when the night side is completely dark and all of the stellar flux is reradiated from the day side, in accordance with the no-redistribution model, and assuming zero albedo. At the right we show the true mass of the planet given the assumed inclination (based on the minimum mass derived from the radial velocity curve), in units of Jupiter masses.
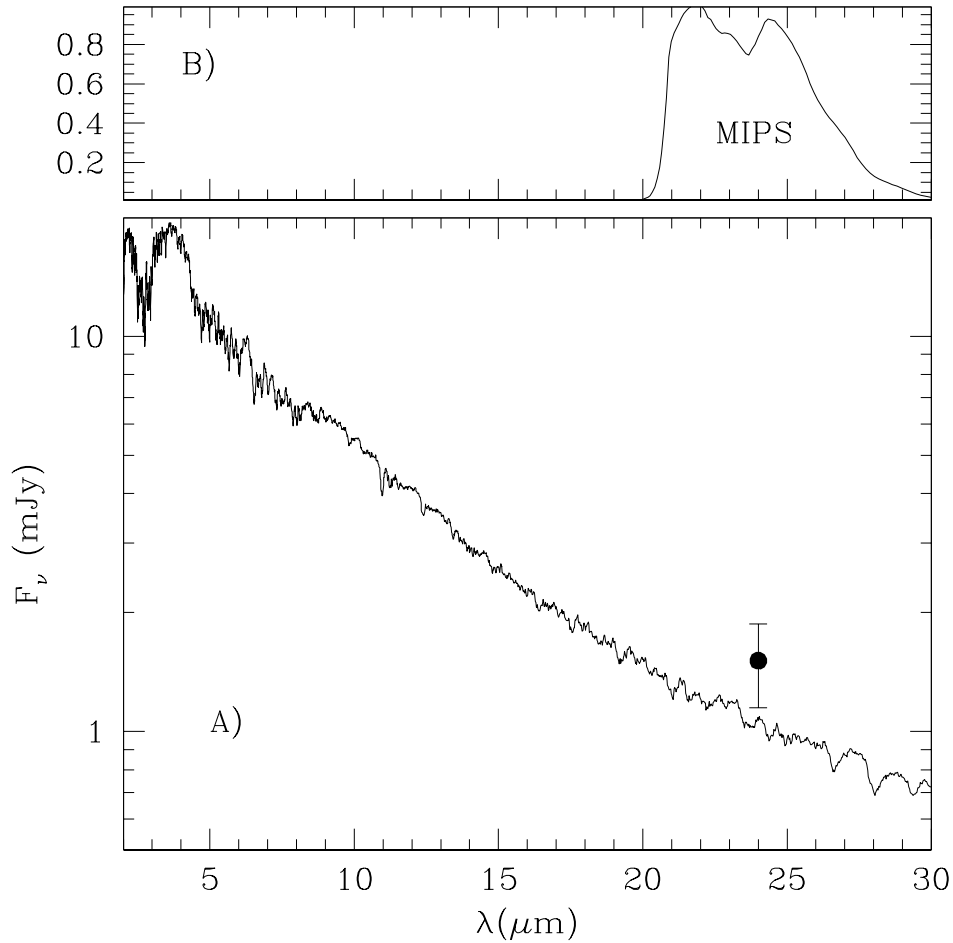
Figure 4: Comparison of the measured amplitude and a planetary spectral model. A) The solid curve shown is a model (*17*) for a planet of radius 1.4 R_{J}, irradiated with parameters appropriate to the υ Andromeda system observed at full phase. This results in a temperature ~ 1977 K (*23*). The model is in agreement with the observations (filled circle) at the 2σ level. B) The normalised spectral response curve of the MIPS 24 μm instrument extends from 20μm to 30μm.