Differential Rotation of the Active G5 V Star $\kappa^1$ Ceti: Photometry from the MOST Satellite

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ABSTRACT.

About 30.5 days of nearly uninterrupted broadband photometry of the solar-type star $\kappa^1$ Ceti, obtained with the MOST (Microvariability and Oscillations of Stars) satellite, shows evidence for two large starspots with different rotation periods of 8.9 and $\sim$9.3 days ($\Delta\Omega/\Omega \approx 4\%$). Ground-based measurements of Ca II H and K emission in 2002 and 2003 reveal variations in chromospheric activity with a period of about 9.3 days. The data were obtained during the MOST commissioning phase. When the data are combined with historical observations, they indicate that the 9.3 day spot has been stable in its period for over 30 yr. The photometry, with a sampling rate of approximately once per minute, was also used to search for acoustic ($p$-mode) oscillations in the star. We detect no clear evidence for $p$-modes in the $\kappa^1$ Ceti photometry, with a noise level around 7–9 $\mu$mag at frequencies in the range of 0.5–4 mHz (3 $\sigma$ detection limit of 21–27 $\mu$mag). There were no flares or planetary transits during 30.5 days of MOST monitoring with light amplitudes greater than 2 mmag (durations $\leq 200$ minutes) and 3 mmag (2–200 minute durations). While this rules out any close-in planets with Jupiter diameters $\leq 0.5$ and orbital inclinations close to $90^\circ$, the scatter in differential radial velocities permit a close giant planet in a more highly inclined orbit.

On-line material: machine-readable table

1. INTRODUCTION

The production of solar flares, the evolution and migration of sunspots, and the very origin of the Sun’s magnetic field are all believed to be associated with differential rotation beneath and at the solar surface. To test models of stellar dynamos, measurements of differential rotation in other stars are nec-
essary for correlation with other parameters, such as magnetic variability and chromospheric activity.

Surface differential rotation (SDR) can be easily observed in the Sun, with detailed observations going back to Carrington (1860); and subsurface rotation has been inferred from helioseismic data of the Sun’s 5 minute p-mode oscillations (e.g., Thompson et al. 1996). However, it is a challenge to observe SDR directly at the surfaces of other stars. With the notable exception of EK Dra, where two spot modulations differing in period by 5.5% are simultaneously visible (Messina & Guinan 2003), evidence for SDR in most solar-type stars with prominent star spots is seen only by comparing data over many years. Light variations ascribed to rotational modulation sometimes change in period from epoch to epoch, and the most natural explanation is that the dominant spot systems appear at different latitudes and move with different rotational periods (e.g., Hall & Bushy 1990; Henry et al. 1995). Doppler imaging of some solar-type stars from epoch to epoch has also revealed evidence for SDR (see reviews by Collier Cameron [2002] and Strassmeier [2004]), and in at least one case (the rapidly rotating K dwarf AB Doradus), SDR was observed in the Doppler maps in only a few consecutive rotations (Collier Cameron et al. 2002). So far, there have not yet been measurements of solar-type acoustic oscillations in any star other than the Sun with sufficient frequency resolution to explore its interior rotation.

The MOST (Microvariability and Oscillations of Stars) satellite (Walker et al. 2003b) was pointed at κi Ceti as part of the commissioning phase of the mission, to obtain useful science during engineering tests and debugging of the MOST systems. Our space-based photometry has sufficient time coverage and precision to reveal SDR that is easily evident even in only three equatorial rotations of the star. The data also set the first meaningful limits on the amplitudes of p-mode oscillations in this star.

κi Ceti was chosen because of (1) its brightness and location in the sky at the time of these tests, (2) previous indications of spot migration and hyperactivity, and (3) its G5 V spectral type, which made it a possible candidate for solar-type oscillations. We describe the star more fully in § 2. The MOST observations are discussed in § 3. The MOST-orbit binned data produce a light curve that reveals the flux rotational modulation of a young, active Sunlike star in unprecedented completeness and precision (§ 4). We are able to relate the photometric modulations of spot visibility to periodic rotational variations of chromospheric activity seen in high-resolution spectroscopic observations of the Ca ii K emission in 2002 and 2003 (§ 5), the latter obtained just before the MOST observations; the same data provided a new, accurate determination of \( \text{V } \sin i \) for the star. In § 6, the full temporal resolution MOST photometry is used to set meaningful limits on the oscillation amplitudes in this star.

2. THE STAR κi CETI

κi Ceti (HD 20630, HIP 15457, HR 996; V = 4.83, \( B-V = 0.68 \)) is a nearby (9.16 ± 0.06 pc; ESA 1997) G5 V dwarf. Its variability, with a period of 9.09 days, was detected by the Hipparcos mission (ESA 1997). Since then, several studies have aimed at reconciling apparent changes in the period; changes that can be explained by different latitudes of spot formation in different years.

As an MK spectral classification standard (Gray et al. 2001), κi Ceti is one of the most frequently observed stars. Although sometimes considered a “very strong lined” late-type dwarf, its metallicity may be only slightly higher than solar ([Fe/H] = +0.05 ± 0.05; for full references, see Heiter & Luck 2003). As far as it has been possible to establish, it is a single star and does not possess any large planets (Halbwachs et al. 2003). Its radial velocity of +18.9 km s\(^{-1}\), combined with the Hipparcos proper motions, leads to a rather moderate spatial velocity relative to the Sun, suggesting young disk population membership (the two available estimates disagree slightly: Gaidos et al. [2000], \( U = -12.7, V = +7.1, W = +2.6 \); and Montes et al. [2001], \( U = -22.4, V = -4.3, W = -5.3 \)).

Güdel et al. (1997) estimated an age of 750 Myr from the relatively rapid rotation of 9.2 days seen in the spot modulation and suggested that the star is a likely member of the Hyades moving group. However, Montes et al. (2001) considered seven moving groups of nearby young stars, but were unable to associate κi Ceti with any of them.

The young age of the star was the reason for Dorren & Guinan (1994) to include κi Ceti in the “Sun in Time” project, which attempts to characterize young solar-type stars in terms of temporal changes taking place, particularly at the epochs before terrestrial life formation (Guinan et al. 2003). In the group of six such stars, with the youngest being 130 Myr old, κi Ceti is one of the most advanced ones, with an estimated age of about 650 Myr in the Dorren & Guinan (1994) study. The difference in age of 100 Myr, compared with 750 Myr of Güdel et al. (1997), can be traced to the current uncertainty of estimates based on the rotation rate. (Note that the 8.9 day rotation period found in this paper can be taken as an indication of an even younger age).

As is observed for stars with activity somewhat moderated with age, the star shows an activity cycle. Baliunas et al. (1995) monitored the narrowband Ca ii H and K chromospheric fluxes photoelectrically from 1967 to 1991, expressing them in terms of the \( S_{\text{s}} \) index. They found a rotational period of 9.4 ± 0.1 days (Baliunas et al. 1983), with a chromospheric activity cycle of 5.6 yr (Baliunas et al. 1995); the quality of the latter determination was described as “fair,” and longer term trends were noted. Using broadband photometry, Messina & Guinan (2002) observed a photometric activity cycle of of 5.9 ± 0.2 yr between 1990 and 1999, with a rotational period of 9.214 days.

On 1986 January 24, Robinson & Bopp (1988) caught the
signatures of a massive flare in He i D₃, which Schaefer et al.
(2000) subsequently estimated had an energy of ∼10^{15} ergs.
Schaefer et al. (2000) speculated that such massive flares on a
single solar-type star might be triggered by the magnetic field
of a close giant planet, such as those in 51 Peg–type systems.
Neither Walker et al. (1995) nor Cumming et al. (1999) detected
any long-term periodic variability over many years in their pre-
cise radial velocity (PRV) measurements, so there exist no dy-
namical perturbations consistent with a close-in giant planet
(unless the orbit is highly inclined). On the other hand, Walker et
al. (1995) did find (their Fig. 2) a rapid RV change of +80 m
s⁻¹ in 1988.5, which was accompanied by an equally rapid in-
crease in chromospheric activity in the Ca ii x8662 line. While
the RV change could be modeled by the close approach of a
giant planet in a highly elliptical orbit, the tight correlation of
the RV with chromospheric activity (both positive and negative
RV excursions) pointed to a change intrinsic to the star. In § 5.4
we point out that within the scatter of existing RV measure-
ments, κ¹ Ceti could harbor such a planet in a close, high-
inclination orbit.

3. THE MOST PHOTOMETRY

3.1. Photometry of κ¹ Ceti

The photometric observations discussed in this paper were
obtained by the MOST microsatellite (Walker et al. 2003b)
between 2003 November 5 and December 5, during the com-
missioning phases of the mission (constraints and limitations of
these phases are described in § 3.2). MOST is Canada’s first
orbiting space telescope, launched in 2003 June to study
(1) acoustic oscillations in solar-type and magnetic peculiar
stars, (2) rapid variability in hot massive stars, and (3) reflected
light from close-in giant exoplanets. The MOST instrument is
an optical telescope (aperture 15 cm) feeding a CCD photom-
eter through a single broadband optical filter (350–700 nm).
Thanks to its polar Sun-synchronous orbit (altitude 820 km),
MOST can monitor stars in a zodiacal band of sky about 54°
wide for up to 8 weeks without interruption. Starlight from
primary science targets such as κ¹ Ceti (i.e., brighter than
V = 6) is projected onto the CCD as a fixed image of the
telescope pupil, covering about 1500 pixels for high photom-
metric stability and insensitivity to detector flatfield and ra-
diation effects on individual pixels. As has already been dem-
strated for Procyon (Matthews et al. 2004), MOST is
capable of reaching a photometric precision of about ±1 part
per million (ppm) in that mode to search for oscillations in
very bright stars.

Despite limitations during commissioning (see § 3.2), the
MOST data of κ¹ Ceti achieved a duty cycle of about 96% over
a time span of 30.5 days (with only three gaps of a few hours
each), with 40 s exposures obtained approximately once per
minute. At the time these data were obtained, this was the
longest uninterrupted observational coverage of any star other
than the Sun. (MOST has since exceeded this duty cycle and
time coverage on other targets, including Procyon [Matthews
et al. 2004].) MOST was designed to be highly stable photo-
metrically over periods of hours, and also self-calibrating (see
the discussion in Walker et al. 2003b); consequently, the mea-
surements are nondifferential. For some primary science tar-
gets, fainter secondary science targets in the adjacent direct-
focus field may allow us to search for systematic drifts in the
photometry, but no such stars were observed with a sufficient
signal-to-noise ratio (S/N) for κ¹ Ceti.

The MOST photometry is performed in a single spectral
band, with a filter about twice as wide as the Johnson V filter
and slightly redward of it (Walker et al. 2003b), without ref-
erence to comparison stars or flux standards. Thus, there is no
direct connection to any photometric system, and hence no
absolute calibration of the MOST photometry. Because of this,
the original data (expressed in analog-to-digital intensity units,
or ADUs) were normalized to unity at the maximum observed
flux of the star, occurring at JD 2,452,953.0. All variation am-
plitudes in this paper are also expressed in these relative units.

To investigate rotational modulation in κ¹ Ceti, the 40 s ex-
posures were binned according to the 101.4 minute orbital
period of the MOST satellite, increasing the S/N per data point
and minimizing the influence of orbital variations in the pho-
tometric background due to stray Earth light. The electronic
version of Table 1 lists the MOST orbit-averaged photometry,
and those points are plotted in the upper panel of Figure 1.

The formal mean standard error of a single data point is
0.77 mmag (770 ppm), which is about twice the error cal-
culated from the detected photon shot noise. The simple av-
erage of 101 individual 40 s integrations would give an error
of ∼100 ppm, which is not far from what is observed as the
actual scatter of about 200 ppm (which includes the intrinsic
variability of the star). Some of the photometric noise is cer-
tainly intrinsic to the star (e.g., granulation variations, given
the star’s activity), and some is undoubtedly due to a non-
Poisson instrumental noise resulting from the significant

| HJD – 2,452,948 | Normalized flux | Background flux |
|----------------|---------------|----------------|
| 0.461914       | 0.986152      | 0.213726       |
| 0.525269       | 0.987092      | 0.209837       |
| 0.598022       | 0.988443      | 0.213698       |
| 0.668823       | 0.989125      | 0.212024       |
| 0.736816       | 0.990238      | 0.210084       |

Note.—Table 1 is published in its entirety as an ASCII file in the electronic
edition of the PASP. A portion is shown here for guidance regarding its form
and content.

a The Julian Date at the effective center of a MOST orbit of 101 minutes.

b The observed flux normalized to the maximum on JD 2,452,953.0.

c The background flux normalized to the maximum of the stellar signal on
JD 2,452,953.0.

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pointing scatter and the removal of the (noisy) stray light background signal (see § 3.2).

The sky background removed from the data shown in Figure 1 varied from about 21% to 25% of the maximum flux measured from the star (on JD 2,452,953); the background variations are plotted in Figure 2. The background light is due primarily to light entering the instrument from the illuminated limb of the Earth, which is exposed to the face of the satellite with the telescope entrance aperture. During commissioning, the MOST team was still investigating the background and exploring ways to mitigate it for future targets (e.g., choosing the optimum “roll” orientation for the satellite). To correct for the sky background, which is modulated with the satellite orbital period, but varies slightly from orbit to orbit, a running averaged background that is phased with the orbital period was subtracted from the data. During the $\kappa^1$ Ceti observing run, the Moon approached to within about 14° of the MOST target field, but we observe no correlation of the sky background with the angular separation of the Moon and the target, or with the lunar phase (see the lower panels of Fig. 2). The main results of this paper are not particularly sensitive to any residual background variations that may be present. Although the sky background variability is probably the fundamental limit to the long-term precision of the $\kappa^1$ Ceti photometry, we note that the 8.9 day period light photometric cycle was highly stable in the final light curve (§ 4.2), indicating that the background was correctly accounted for in the MOST data over the duration of the $\kappa^1$ Ceti observing run.

3.2. Nature of the Commissioning Science Observations

A brief description of the “commissioning” observations is given below as a record and explanation of certain limitations of these observations compared to the normal scientific operations of MOST, which were initiated in 2004 January, not long after the $\kappa^1$ Ceti data were obtained.

The precise photometry that MOST was designed to obtain is based on integrating the signal in a large image of the telescope pupil (covering about 1500 pixels of the CCD) projected

Fig. 1.—Top: Light curve of $\kappa^1$ Cet obtained from 30.5 days of continuous observations with MOST. The points are averages over the 101.4 minute orbital period of the satellite. The variable background from Earth light has been subtracted. The data are presented as relative signal normalized to the maximum flux observed during the run. The solid curve is the best fit of a simple single-spot model to the dominant 8.9 day variation in the data (see § 4.3 and Fig. 4). Middle: Residual variation after subtraction of the 8.9 day model curve plotted in the top panel shows clear variations whose minima are spaced by about 9.3 days (see § 4.2). Bottom: Predicted variation of the Ca ii K-line emission flux based on the spectroscopic observations obtained only 2 months before the MOST run (see § 5.3 and Fig. 9).

Fig. 2.—Top: Variable sky background measured during our observations, expressed as a fraction of the maximum stellar signal on JD 2,452,953. This background is primarily due to stray light entering the instrument focal plane from the illuminated limb of the Earth. Bottom: Angular separation of the Moon from the star and the corresponding lunar phase during the MOST observations. There is no evident correlation with the sky background in the top panel.
by a Fabry microlens and field stop enclosing the incoming stellar beam. In normal operations, a resolved subraster of the CCD with that pupil image is downloaded for every science exposure, along with Fabry images of the adjacent sky backgrounds, for processing on the ground; this is known as Science Data Stream 2, or SDS2. As a data backup, we also perform the pupil image signal integrations onboard the satellite and store that information there for several days, in case of extended loss of contact with our ground station network; these data are part of Science Data Stream 1 (SDS1).

During commissioning, there was an unrecognized problem with a small fraction of the onboard memory, which led to computer crashes occurring roughly every 1–2 days if both SDS2 and engineering telemetry were being sent to Earth. This resulted in a fraction of the data, about 21%, sent as the fully resolved SDS2 files; the rest of our \( \kappa^1 \) Ceti photometry is based on SDS1 data. The lack of spatially resolved Fabry image data restricts our options of sky background and stray-light removal. However, our later experience (see Matthews et al. [2004] for an example with Procyon) shows that the quality of SDS1 photometry is comparable to SDS2, although the latter is preferred. Even with our routine of downloading only SDS1 data, the onboard memory problem led to occasional computer crashes, which interrupted the data flow for one or more satellite orbits at a time, and accounts for most of the gaps in the light curve of Figure 1. The corrupt memory locations have since been identified, and we avoid storing data there, so this problem no longer affects the MOST mission.

At the commissioning phase of the mission, we had not yet optimized the spacecraft pointing. The mean pointing errors were 4.5' rms in \( x \) and 6'2" in \( y \), so this image wander across the Fabry microlens (with a field stop radius of 30") led to larger photometric errors than were later obtained during normal scientific operations. This also limited our ability to center the target within the field stop. Jitter of the star within the field stop increases noise. These are no longer serious issues for MOST. Upgrades to the attitude control system software have led to steady improvements in pointing. Observations of Procyon in 2004 January–February were made with pointing errors of 1'3 and 3'1 rms in \( x \) and \( y \), respectively; the current pointing performance has been improved to about 1.0 rms in both axes.

### 4. SPOT VARIABILITY AND EVIDENCE FOR SURFACE DIFFERENTIAL ROTATION

#### 4.1. Photometry of \( \kappa^1 \) Ceti before MOST

The current explanation of the variability observed in \( \kappa^1 \) Ceti is that stellar spots cause light changes at the level of 0.02–0.04 mag. The changes have been noted by several ground-based observers as having characteristic timescales of about 9 days. The most extensive studies were done by Gaidos et al. (2000) and Messina & Guinan (2003). From 20 years of literature data, Gaidos et al. (2000) found several periods ranging between 9.14 and 9.46 days, each with uncertainty at the level of 0.03–0.05 days. Messina & Guinan (2003) conducted a careful study over six seasons and determined individual periods ranging between 9.045 and 9.406 days, with typical uncertainties of 0.02–0.05 days. The simplest explanation for such period changes is that spots are forming at or migrating to different stellar latitudes that are rotating with different angular velocities.

By relating the spot modulation periods to the photometric cycle, Messina & Guinan (2003) suspected that \( \kappa^1 \) Ceti shows an “antisolar” pattern in which the period of the rotation modulation tends to increase steadily during the activity cycle.

#### 4.2. Interpretation of the MOST Photometry

The photometric data discussed here consist of orbit-averaged observations (binned by intervals of 101.4 minutes), corrected for sky background, as presented in Table 1 and the upper panel of Figure 1. A double-wave variation is clearly evident, consisting of deep minima with a depth of about 0.04 of the maximum light, interspersed with moderately shallow depressions with amplitudes of about 0.005–0.01. The shallow minima progressively move relative to the deeper ones, as if two close periodicities were involved.

The photometry only covers about three cycles of the dominant variation, so Fourier analysis is relatively ineffective at accurately identifying the periodic content of the variations. We formally recover two significant peaks at frequencies of 0.1146 and 0.2170 day\(^{-1}\), corresponding to periods of 8.72 and 9.22 days (actually, 4.61 = 1/2 × 9.22). Because of the short duration of the observing run, these periods cannot be established to better than about ±0.1 day (Fig. 3). Instead of using the formal values of the derived periods, we use two periods, 8.9 and 9.3 days, which are derived by a simple folding of the data in a sequential decomposition of the light curve, starting from the largest and most regular variation.
1. The most obvious is a periodic pattern reminiscent of an eclipsing light curve or a spot curve—the latter due to a spot or a group of spots with probably well-defined edges covering a moderately large fraction of the stellar surface. This pattern has an amplitude reaching 0.04 of the maximum observed flux and a period of 8.9 ± 0.1 days. An average of three cycles gives a relatively stable light curve, as shown in the phase diagram of Figure 4.

2. When the 8.9 day pattern is removed, another periodic variation becomes visible. This is shown in the middle panel of Figure 1. This pattern is less regular than the 8.9 day variation, with the minima becoming progressively deeper from about 0.005 to 0.01 over the three complete cycles. (There is evidence that the next cycle, which is incomplete, is shallower than the preceding one.). The three times of minima give an approximate period of 9.3 days, where the uncertainty is harder to estimate, because of the variable shapes of the dips.

3. The middle panel of Figure 1 suggests that either the 9.3 day pattern evolved over time, or there existed residual variability from some other source, especially at the beginning of the MOST run. The variability was most probably intrinsic to the star, judging by the progression of the depths of the 9.3 day pattern and the excellent agreement between the phased minima of the 8.9 day pattern. We observe no correlation between the sky background variations (shown in Fig. 2) and the deviations from the regular 9.3 day periodic pattern, shown in the middle panel of Figure 1; this may be taken as an indication that the sky background variations were not the cause of these irregularities.

4.3. Spot Modeling

The observed periodic variations can be explained by spots formed at different stellar latitudes and carried by the rotation of the star at different angular velocities. With single-band photometry, little can be said about the type of spots, whether they are hotter or cooler than the surrounding photosphere. However, two of the authors did develop two simple, entirely independent geometric spot models to try to reproduce the observed light curve. The models differed in approach, in that the first used the minimum number of parameters and ended up describing only the larger spot, which apparently did not fit the primary variation to better than 0.001 (Fig. 4). The second model was underconstrained, but its basic results fully confirmed the first model in its description of the larger spot.

In the simplest terms, the larger of the two spots, with a rotational period of 8.9 days and a relative flux amplitude of 0.039, if entirely black and circular, would have a radius of 19% of the stellar radius, or an angular radius from the star center of 11°. The mean 8.9 day light curve is shown in Figure 4. Since the light variations take place over slightly more than half of the rotation, and the “flat top” is shorter than half of the rotation, the spot appears to be situated above the equator. The smaller spot, causing the 9.3 day (or slightly longer) periodicity, also if black and circular, must be about 12% of the stellar radius (angular radius 7°).

Any model must face the limitation that the parameter without any constraint is the unperturbed level of the light curve, \( l_0 \); we arbitrarily assumed it to be at the highest observed level (see Fig. 1), but some small spots may have been present on the surface at all times. While the spot longitude \( \lambda \) can be removed from the parameter list by an appropriate adjustment of the phases, even the simplest model involves several adjustable parameters: the rotation axis inclination \( i \), the limb-darkening coefficient \( u \), the latitude \( \beta \), the size or the angular radius as seen from the center of the star \( r \), in addition to the darkness \( t \) of the spot. The darkness (0 ≤ \( t \) ≤ 1) of the spot cannot be estimated from the single-color data, so that the minimum size of the spot can be estimated assuming a black spot (\( t = 0 \)). Even such a highly simplified model, with several parameters fixed, contains at least three fully adjustable geometrical parameters: \( i \), \( \beta \), and \( r \). The best model of the larger spot fits the primary variation to better than 0.001 (Fig. 4). The relevant parameters for the star and the larger spot (where the symbol \( \equiv \) means a fixed parameter) are \( P = 8.9 \pm 0.1 \) day, \( i = 70° \pm 4° \), \( \beta = +40° \pm 7° \), \( r = 11°1 \pm 0°6 \), \( \lambda \equiv 0° \), \( t \equiv 0 \), and \( u \equiv 0.8 \). The 8.9 day spot is relatively large and may be larger if not entirely black, so the assumption of it being circular—especially in view of the clear evidence of the shearing differential rotation—is highly disputable. Therefore,
this solution should be taken as indicative, rather than of much physical significance.

The second model assumed two independent spots with different rotational periods. It was specified by the rotational inclination \( i \) of the star and the limb-darkening parameter \( u \), with all parameters describing the two spots: the radii and flux contrasts read and the latitude, initial longitude, and the rotation period for each spot. Such a model required extensive tests of different combinations of parameters. While the results are inconclusive in details because of the large number (12) of weakly constrained parameters, they are fully consistent with the minimum-parameter model described above in the description of the first (8.9 day) spot. The second spot in the extended model appears to have a longer period, perhaps as long as 9.7 days, although uncertainty of the period is large and results from the obvious evolution of the second spot over time and a complex coupling with values of the remaining parameters.

The models have been unable to define accurate latitudes of both spots, although the second, more complex model suggested a higher latitude for the smaller, 9.3 day spot—a situation that would correspond to the solar surface differential rotation pattern. However, there is no question from both independent analyses that the two spots have unambiguously different periods, supporting the interpretation of SDR with \( \Delta f / f = 4\% \). This is clear evidence of surface differential rotation on \( \kappa^1 \) Ceti, and only the second after EK Dra (Messina & Guinan 2003) in which two spots were also simultaneously visible. All other inferences were based on apparent period changes (Hall & Busby 1990; Henry et al. 1995; Gaidos et al. 2000; Messina & Guinan 2003), the interpretation of subtle broadening effects in spectral lines, so far detectable only in the most rapidly rotating stars (Donati & Collier Cameron 1997; Donati et al. 1999), or Doppler imaging from epoch to epoch (Collier Cameron 2002). (For general reviews of these techniques and their limitations, see Rice [2002], Gizón & Solanki [2004], and Strassmeier [2004]).

### 4.4. Searching for Flare Activity and Transits

The MOST orbit-averaged data were also searched for short-lived variations that might be associated with transits of a close-in giant planet or with white-light flares. The latter seemed more likely, given the history of activity of \( \kappa^1 \) Ceti. No candidates for transits or flares were found in the data. We can set useful limits on such events over the month that we observed the star. There were no flare events or transits with peak-to-valley variations of more than 2 mmag with durations longer than 200 minutes, and none with variations greater than 3 mmag with durations between 2 and 200 minutes.

For planetary transits, this limits the size of any possible transiting bodies with orbital periods of about 30 days or less to approximately 0.045–0.055 of the stellar radius, about half the size of Jupiter. However, our spot modeling and measurements of \( V \sin i \) indicate that the rotational inclination of the star is not close to 90°, so it is not expected that the orbital plane of any planets in the \( \kappa^1 \) Ceti system would be coincident with the line of sight.

## 5. GROUND-BASED SPECTROSCOPY

### 5.1. The CFHT Spectroscopic Observations

Several of us (D. B., S. R., E. S., and G. W.) monitored the Ca II H and K reversals of a number of 51 Peg systems (Shkolnik et al. 2003), in addition to several active, single stars using the Gecko spectrograph on the Canada-France-Hawaii 3.6 m Telescope (CFHT). The intention was to detect chromospheric activity synchronized with the planetary orbits. As a by-product, we determined radial velocities for these stars, with \( \sigma_{\text{sys}} \leq 20 \text{ m s}^{-1} \) (Walker et al. 2003a). Here we present the various results for \( \kappa^1 \) Ceti.

The dates of the observations are listed in Table 2. They were acquired on four observing runs in 2002 and 2003 with the Gecko coupled spectrograph, which was fiber-fed from the Cassegrain focus of the CFHT. Single spectra were recorded at a resolution of 110,000 spanning 60 Å and centered at 3947 Å (see Fig. 5). The S/N was \( \approx 500 \) per pixel in the continuum and 150 in the H and K cores. Full details of the data reduction are given in Shkolnik et al. (2003).

### 5.2. Determination of \( V \sin i \)

\( \kappa^1 \) Ceti shows moderate broadening of lines due to rotation at the rate of about 9 days. The broadening is detectable in our high-resolution spectroscopy. Combined with the rotation period and the value of the radius, \( V \sin i \) can be used to set a constraint on the rotational axis inclination \( i \), which is one of the free parameters in the spot models. The previous determinations of \( V \sin i \) were 3.9 km s\(^{-1}\) (Fekel 1997), 4.3 km s\(^{-1}\) (Benz & Mayor 1984), 5.6 km s\(^{-1}\) (Soderblom et al. 1989), and 3.8 km s\(^{-1}\) (Messina et al. 2001).

We determined the value of \( V \sin i \) by analyzing the broadening of the photospheric lines in the region of Ca II \( \lambda\lambda3933/3968 \) in our CFHT spectra. We used the broadening function formalism (Rucinski 1999, 2002) of the deconvolution of photospheric spectra of rotating stars with spectra of sharp-line, slowly rotating stars. The approach leads to the removal of all common agents of line broadening, not only of the instrumental component, but also of the tangential turbulence and of all other components that are the same for the program and the template stars. For \( \kappa^1 \) Ceti, we used \( \tau \) Ceti, which is a slightly cooler dwarf (G8 V) that rotates very slowly (\( V \sin i = 0.6 \text{ km s}^{-1} \); Fekel 1997).

For the determination of the broadening function, the spectra must be rectified and normalized. As shown in Figure 5, the rich photospheric spectrum in both \( \kappa^1 \) Ceti and \( \tau \) Ceti is superimposed on strongly variable far wings of the Ca II absorption. We removed sections of the spectrum where the wings...
fall below $\frac{1}{2}$ of the maximum flux, and applied a simple, upper-envelope rectification between high points of the quasi continuum. Figure 6 shows the broadening function for one of the CFHT spectra, obtained on 2003 August 26 (see Table 2). Instead of least-squares fits of the limb-darkened rotational profile (Gray 1992) to the broadening functions (with the limb-darkening coefficient assumed to be $u = 1.0$, appropriate for the UV in late-type stars), we matched the half-widths at half-maximum; such $V \sin i$ determinations are less sensitive to the residual uncertainties at the base of the broadening function. Our average $V \sin i = 4.64 \pm 0.11$ km s$^{-1}$ is compatible with previous determinations. We note that Gaidos et al. (2000), using an almost identical value of $V \sin i = 4.5$ km s$^{-1}$, interpreted it as implying $40^\circ < i < 90^\circ$. The main spot in both model fits is located at a moderate stellar latitude above the equator. If the period of $8.9 \pm 0.1$ days were ascribed to the stellar equator, then the best-fitting inclination of $i = 60^\circ \pm 5^\circ$ and the measured $V \sin i$ combine to give a stellar radius of $R \approx 0.95 \pm 0.10 R_\odot$, which is certainly reasonable for a G5 V star.

### 5.3. The K-Line Residuals

The 7 Å region centered on the K line that was used in the analysis is shown for a single spectrum in Figure 7, where spectral intensity is normalized to unity at the wavelength limits. In Figure 8 the residuals from the average normalized spectra are shown for each night (where pairs of spectra on the same night have been averaged). Activity is confined entirely to the reversals, within about 0.94 Å around the center of the emission core, or within $\pm 35.8$ km s$^{-1}$. If this broadening is caused by the velocity field, it is some 7.7 times larger than $V \sin i$. To visualize the changes in the reversals, the integrated flux residuals shown in Figure 9 are expressed in Å relative to the restricted continuum height shown in Figure 7. This height corresponds to about one-third of the local photospheric continuum around the Ca II lines, so that the integrated residuals are proportional, but not identical, to the emission equivalent width. They are listed in column (4) of Table 2.

The best-fitting periodic variation for the K residuals in Table 2 over the four observing runs in 2002 and 2003 has a period of 9.332 $\pm$ 0.035 days. The residuals are plotted as a function of phase in Figure 9, with the arbitrary initial epoch of the minimum residual flux at $T_0$ (HJD) = 2,452,485.117 (the minimum flux epoch can be estimated to be $\pm 0.1$ days). The data from 2002 are shown as open symbols, and those from 2003 September are solid. Although the data from 2002 cover only three rotations, with the data from 2003, the span in the rotations is extended to 44.

Since the period is largely defined by the 2002 observations, Figure 9 implies that the rotation associated with the enhanced Ca II activity has remained quite stable. The 9.332 day period is entirely compatible with that found by Baliunas et al. (1983; 9.4 $\pm$ 0.1 day), suggesting that the enhanced activity has in fact been stable at the same latitude for at least 36 yr (over 1400 rotations). This period is also compatible with the 9.3 day period of the less prominent spot that we see in the MOST observations (see § 4.2). Given this apparent stability, it is reasonable to extrapolate variations in the K-line residuals to the epoch of the MOST photometry that corresponds to only seven additional rotations. The bottom panel of Figure 1 shows the K-line flux changes that can be related to the photometric
Fig. 5.—Typical CFHT spectra of $\kappa^1$ Ceti and of $\tau$ Ceti, expressed as normalized flux vs. wavelength; the latter star served as the sharp-line template. The broadening functions for $\kappa^1$ Ceti were determined from the upper parts of the photospheric spectra after removal from the spectra of the lower parts close to the cores at $<1/3$ of the maximum height.

Fig. 6.—Broadening function for $\kappa^1$ Ceti, determined relative to $\tau$ Ceti for one of the CFHT spectra. The broadening function gives a one-dimensional image of the rotating star, projected into the radial velocity space; it can be used for the determination of the value of $V \sin i$. The broadening function is dimensionless, and—for perfect match of the spectral types—its integral equals unity. The thin line shows the intrinsic spectral resolution of the method, while the broken line gives the calculated rotational profile for $V \sin i = 4.64$ km s$^{-1}$ and the limb darkening of $u = 1.0$. The spike in the center shows the intrinsic resolution of the technique.

Fig. 7.—Ca $\text{ii}$ K-line emission reversal, normalized at the ends of the spectral window in a single typical CFHT spectrum.

5.4. The Radial Velocities

Radial velocities were estimated from $\approx 20$ $\text{Å}$ of the photospheric spectrum (3942–3963 $\text{Å}$; see Fig. 5) using the fxcor routine in IRAF$^3$ with Th/Ar comparison lines providing dispersion correction (more detail is given in Walker et al. 2003a). The first spectrum of the series in 2002 acted as the template from which differential radial velocities ($\Delta RV$) were measured for all the spectra. The $\Delta RV$ values are listed in Table 2, plotted against the 9.332 day rotational phase determined from the K-line residuals in Figure 9, where the open symbols correspond to data from 2002, and the solid points to 2003 Septem-

$^3$ IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., (AURA) under cooperative agreement with the National Science Foundation.
Fig. 8.—Residuals from the Ca ii K-line mean averaged normalized profile, as shown in Fig. 7, for individual nights, with one to three observations averaged if close in time. Note that all changes are strictly confined to the Ca ii emission reversal. The phases of the 9.332 day periodicity are given in the legend; they correspond to those in Table 2, where individual observations are listed.

Fig. 9.—Top: Integrated residuals of the Ca ii K-line emission expressed in Å and plotted vs. the 9.332 day rotation phase. Data points from 2002 are marked by open circles, while those from 2003 are shown as solid circles. Bottom: Radial velocity deviations from the first spectrum. There is a remarkable consistency between the ΔRVs from both years, suggesting that the underlying ΔRV technique is highly stable even without an imposed fiducial (such as iodine vapor).

From the 2002 data, we derive $\sigma_{RV} = 21.8$ m s$^{-1}$ and $23.6$ m s$^{-1}$ when combined with 2003. These values are very similar to the $\sigma_{RV} = 24.4$ m s$^{-1}$ found over 11 yr by Cumming et al. (1999). For comparison, a planet that induces a reflex radial velocity variation below 50 m s$^{-1}$ and is tidally synchronized to the star would have $M \sin i = 0.74M_J$ and $a = 0.084$ AU. Consequently, $\kappa^1$ Ceti could still harbor a giant planet in a tidally locked orbit, which we would not have detected.

In 2003 the ΔRVs appear significantly different between the two nights, which seems to be reinforced by the consistency within the pairs of ΔRVs. While a planetary perturbation cannot be ruled out by the 2002 data and other PRV studies, the difference in 2003 might be associated with the velocity field of the star itself. The increase of velocity with increasing K-line strength is consistent with the extreme event in 1988.5 seen by Walker et al. (1995). However, the data are insufficient to further discuss the point here.

6. ABSENCE OF Π-MODE OSCILLATIONS

In Figure 10, we present the Fourier amplitude spectrum of the complete set of unbinned photometry (at a full temporal resolution of about 1 minute) in which the lower frequency modulations have been filtered from the data. Also, the known

Fig. 10.—Fourier amplitude spectrum of the unbinned MOST photometry with 40 s integrations and 1 minute sampling interval. The maximum frequency in this plot (4 mHz) corresponds to a period of 250 s; there is no noticeable change in noise level nor any signals evident at frequencies up to the Nyquist frequency of about 8 mHz. The amplitudes for frequencies corresponding to the satellite orbital frequency and its harmonics have been removed to avoid any contamination by orbital modulation of the stray light background. The dashed line is the formal 1σ noise level in the spectrum.
satellite orbital frequency and its harmonics have been removed from the data to avoid any confusion with residual stray light variations. Although the spectrum is only plotted to a frequency of 4 mHz (period = 4.17 minutes), the noise is leveled out to the Nyquist frequency of about 8 mHz, and there are no significant periodic signals detected in that range. The white dashed line represents the theoretical Poisson noise for the data.

Although there are a few peaks visible at frequencies below 1 mHz, there is no evidence for the pattern of nearly equal spacing associated with $p$-mode oscillations of low degree and high overtone (as seen in the Sun). There are several isolated peaks in the range of 0.1–1.0 mHz (periods of 2.8 hr to 17 minutes) that may be real but are too few and too widely separated to attempt a meaningful fit to a model.

At a detection level of 3 $\sigma$, we exclude coherent oscillations larger than about 27 ppm around 1 mHz, 26 ppm at 2 mHz, and 24 ppm at 3 mHz. (The last is in the frequency range of the solar oscillations.) Thus, we would not expect to detect $p$-mode oscillations in $\kappa^1$ Ceti if they were at the level observed in photometry of integrated light of the Sun (i.e., about 4–10 ppm; Fröhlich et al. 1997).

However, knowledge of the nature of $p$-mode oscillations in other stars is very limited, and the first space-based photometry of Procyon obtained with MOST by Matthews et al. (2004) yielded an unexpected null result despite a detection limit at least twice as good as in these commissioning data for $\kappa^1$ Ceti. We are only beginning to explore the characteristics of $p$-mode oscillations in luminosity for stars beyond the Sun. The moderately young age of $\kappa^1$ Ceti, its relatively rapid rotation compared to the Sun, and its later-than-solar spectral type may be contributing factors to the absence of large-amplitude (i.e., >20 ppm) $p$-modes in this star.

7. CONCLUSIONS

We have presented data on the photometric and spectroscopic variability of the moderately young, solar-type star $\kappa^1$ Ceti. We describe our continuous photometric observations over 1 month in 2003 November using the MOST satellite, in addition to high-resolution spectroscopic CFHT observations over four observing runs in 2002 and 2003. The MOST data (averaged over the 101.4 minute orbital period of the satellite) have an estimated point-to-point accuracy of $\sim 0.2$ mmag, or $\sim 200$ parts per million, and an unprecedented temporal coverage of 30.5 days, with a completeness of 96%.

The MOST orbit-averaged photometry of $\kappa^1$ Ceti shows two distinctly different periodicities—a well-defined 8.9 day variation and a smaller, less regular variation whose period appears to be around 9.3 days or slightly longer. The best interpretation of these variations is that two spots (or compact spot groups) are at different latitudes on the stellar surface, moving at angular rates that are different by $\Delta\Omega/\Omega \approx 4\%$. This is one of the most direct evidences of surface differential rotation in a cool star other than the Sun, and the second such after EK Dra (Messina & Guinan 2003). All other measurements of SDR in other stars have been more indirect, either through season-to-season variations in spot period variability, or through subtle broadening effects in spectral line profiles, so far observable only in the most rapidly rotating stars.

The details of the smaller, slower moving spot on $\kappa^1$ Ceti depend on how one describes and removes the larger spot (8.9 day) variability and on the treatment of the slowly varying residuals. The multiparametric modeling of the spots suggests that the smaller spot is located at a higher latitude, which would suggest a solar-like SDR pattern. However, independent spectroscopy of the star, some of which was obtained only a few variation cycles before the MOST photometry, reveals that maxima of the Ca $\textit{H}$ K-line emission reversals are synchronized with a period of about 9.3 days, lending support to that period identification for the second spot. While showing significant evolution in size, shape, and/or flux contrast even during our month of observations, the 9.3 day spot may in fact be the more stable one, and perhaps visible over decades, based on earlier observations of $\kappa^1$ Ceti in the literature. The shorter, 8.9 day periodicity suggests that $\kappa^1$ Ceti rotates faster than previously supposed and thus may be even younger, based on the correlation between equatorial rotation period and age in solar-type stars.

The unbinned MOST photometry, with an integration time of 40 s and a sampling of once per minute, sets limits on (1) the presence of $p$-mode oscillations, (2) the eruptions of flares over 1 month of monitoring of this historically active star, and (3) the occurrence of planetary transits in the system. The data effectively rule out $p$-mode oscillations larger than 25 ppm at the 3 $\sigma$ limit. There were no flares with durations from 2 to 200 minutes whose white-light amplitudes could be larger than 2–3 mmag. There can be no planets with orbital periods shorter than 30 days larger than about 0.5 Jupiter diameter in an orbit plane that would lead to transits as seen from Earth. Within the value of $\sigma_{rv} \sim 23$ m s$^{-1}$ that we have determined, there could be a close Jupiter-mass companion in an inclined orbit.

The information gleaned from this early set of MOST data, obtained before the satellite performance was optimized for normal operations, and on a target that was not part of the original planned scientific program, indicates the tremendous power of precise, nearly continuous photometry spanning many weeks, which is possible from a dedicated instrument in the right orbit in space. There are many more applications like the ones described in this paper, and instruments like MOST can be an effective tool in studying the surface properties of rapidly rotating solar-type stars.

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