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TITLE: **Long-term Doppler Shift and Line Profile Studies of Planetary Search Target Stars**

ORGANIZATION: The University of Arizona
Lunar and Planetary Laboratory

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PROJECT SUMMARY

This grant supported attempts to develop a method for measuring the Doppler shifts of solar-type stars more accurately. The expense of future space borne telescopes to search for solar systems like our own makes it worth trying to improve the relatively inexpensive pre-flight reconnaissance by ground-based telescopes. The concepts developed under this grant contributed to the groundwork for such improvements. They were focused on how to distinguish between extrasolar planets and stellar activity (convection) cycles.

To measure the Doppler shift (radial velocity; RV) of the center of mass of a star in the presence of changing convection in the star's photosphere, one can either measure the effect of convection separately from that of the star's motion and subtract its contribution to the apparent RV, or measure the RV in a way that is insensitive to convection. This grant supported investigations into both of these approaches. We explored the use of a Fabry-Perot Etalon (FPE) interferometer and a multichannel Fourier Transform Spectrometer (mFTS), and finished making a 1.8-m telescope operational and potentially available for this work.

PUBLICATIONS

The names of Project personnel are in bold face type.

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Abstract. *Bull. Amer. Astron. Soc.* **32,** 1042-1043. Progress on the Spacewatch 1.8-m telescope and upgrade of the Spacewatch 0.9-m telescope.

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DESCRIPTION OF THE PROBLEM

The method being addressed is the detection of small, slow changes of stellar Doppler shifts (radial velocities; RV's) induced by the orbital motion of planets about stars. By surveying large numbers of stars, various investigators have discovered substellar companions to solar-type stars (Latham *et al.* 1989; Mayor and Queloz 1995; Mazeh *et al.* 1996; Marcy and Butler 1996; Butler and Marcy 1996; Cochran *et al.* 1997). With the notable exception of 47 UMa (Butler and Marcy 1996), the companion of which orbits with a 3 yr period, the small orbits of these companions are uncharacteristic of our solar system and seem to exist around only 3% of the stars surveyed (Mazeh *et al.* 1996, Marcy and Butler 1996). Around the rest of the stars, the frequency of occurrence and detailed character of planetary systems, with much smaller RV amplitudes and much longer periods, are still unknown and will require more exacting work to be revealed. This also applies to planets in larger orbits about the stars that have already been found to have short-period companions.

Our purpose is to make RV a more reliable measure of small-amplitude, long-period variations of the motion of a star. Small (<10 ms^{-1}) variations of RV with multi-year periods in solar-type stars can be difficult to distinguish from the effects induced on spectral lines by stellar activity cycles (Dravins 1982, 1985; Saar and Donahue 1997). This ambiguity is due to the similarity of time scales of planetary orbits and stellar activity ("spot") cycles (Wilson 1978, Baliunas *et al.* 1995), combined with the fact that changes of convection can, under some conditions of measurement, alter the apparent RV of some stellar absorption lines. This modulation of stellar line profiles by convective cycles was predicted qualitatively by Dravins (1982, 1985, 1992) and quantitatively by Saar and Donahue (1997). It has been observed in absorption lines in the photosphere of the sun by Livingston (1987, 1991), Deming and Plymate (1994), and Livingston *et al.* (1999), and in other stars by Gray and Baliunas (1995) and Gray *et al.* (1996). Saar, Butler, and Marcy (1998) and Saar and Fischer (2000) show correlations of the residual dispersion of stellar RVs with a chromospheric activity index.

The conventional wisdom is that absorption lines in convective photospheres are asymmetric because the gas rising in granules is hotter than the gas descending in the intergranular lanes. Both masses of photospheric gas contribute to the spectrum of the star observed as a point source, but unequally in flux due to their temperature difference and unequally in apparent RV due to the difference in projected line-of-sight velocity between the rising and falling material. The efficiency of granular convection is affected by a weak magnetic field that pervades the photosphere (Livingston *et al.* 1999). The stronger field during activity maximum makes the granules smaller with respect to the intergranular spaces and also reduces the difference in velocity between the rising and falling cells of gas. Therefore photospheric absorption lines tend to be slightly less asymmetric during activity maximum.

There are complications to the conventional picture of convection; the effects on the lines may be out of phase with the activity cycle depending on how much of the surface of the star is normal granular photosphere and how much is faculae and spots (Gray 1994), so it is not easy to predict the magnitude of the effect on apparent RV. In the search for "Jupiters" (extrasolar planets with both the mass and the orbital parameters of Jupiter), avoiding stars with active chromospheres would severely limit the region of the HR diagram being explored. Avoidance of stars with RV "jitter" caused by active chromospheres may also tend to bias RV surveys in favor of pole-on systems (Han *et al.* 2001). Additionally, dwarf stars cooler than the Sun are numerous among the nearest stars, and chromospheric activity is common among such stars. The analysis of a long-period variation of the RV of ϵ Eridani, for example, was complicated by the star's cyclic activity (Hatzes *et al.* 2000). Therefore RVs of the most attractive *astrometric* targets are especially vulnerable to changing convection in the stars' atmospheres.

SOLUTIONS TO THE PROBLEM

Analyzing the Effects of Convection:

When stellar absorption lines subjected to convective modulation are observed at the resolutions commonly used for RV work, they can appear to shift in wavelength as if the star's RV were changing (Dravins 1982, 1985; Saar and Donahue 1997). The shape of the bisector of the profile of an absorption line is the usual empirical measure of line asymmetry. Variation of line bisectors through almost two complete activity cycles have been observed in the Sun by Livingston *et al.* (1999). Gray and Baliunas (1995) observed a multi-year cyclic variation of line bisectors in ϵ Eridani. Gray *et al.* (1996) showed the time dependence of line bisectors of ξ Bootis A (HR 5544A) during variations of its chromospheric activity.

However, there have not been many direct measurements of the effect of convective cycle changes on apparent RV. Comparison between the work of McMillan *et al.* (1993) and Deming and Plymate (1994) on the Sun shows the sensitivity of such results to which lines are chosen and how the lines are measured. While Deming and Plymate observed a variation of apparent RV during the solar cycle by observing lines at 2.3 microns, McMillan *et al.* (1993) established a new upper limit on the variability of the RV of the integrated disk of the Sun as measured from the steep flanks of photospheric absorption lines in violet light.

Dravins (1992) argued that a resolving power $R = \lambda/\Delta\lambda > 300{,}000$ is required to accurately represent the shapes of line bisectors. To be sure, *changes* of apparent RV large enough in amplitude can be detected with R as "low" as 50,000. Saar, Butler, and Marcy (1998) showed correlations of the residual dispersion of RVs of 17 stars with stellar temperature, Ca II HK emission, and rotational speed. Gray (1994) and Gray *et al.* (1996) measured line bisectors with R=100,000. However, the adequacy of R=100,000 can be questioned (Dravins 1987, Gray 1998, Hatzes *et al.* 1998). Saar and Fischer (2000) derived empirical corrections to RVs of stars based on a correlation of apparent RV and a Ca II emission line index, but a more direct approach is to analyze the line profiles themselves.

We are seeking true bisector shapes and high sensitivity to bisector changes to make it possible to compare the data with models. R=300,000 may seem extravagant, but it merely provides 1 kms^{-1} resolution, and the Sun rotates with an equatorial surface speed of only 2 kms^{-1}. There are also other line broadening mechanisms with similar widths acting at the same time, and to deconvolve them from each other and from the instrumental broadening function, the latter needs to be not only narrow but also stable, smooth, and symmetrical. Dravins also prescribed high signal-to-noise ratio, high instrumental contrast, and low instrumental wings to analyze line profiles for convectively-driven changes (Dravins 1978, 1987, 1992).

Resolving power this high is rare in stellar spectroscopy, and even rarer with low enough wings to provide the true shapes of line profiles (Dravins 1978, 1987). A spectrometer with R=300,000 would complement the programs of Mayor and Queloz (1995) and Baranne *et al.* (1996) at Haute Provence (R=42,000), Butler and Marcy (1996), Marcy and Butler (1996), Butler *et al.* (1996), and Cumming *et al.* (1999) at Lick (R=60,000), Brown *et al.* (1994) at Mt Hopkins (R=70,000), Vogt *et al.* (2000) at Keck (R=80,000), UCLES at the Anglo-Australian Observatory (AAO; R=80,000), Gray *et al.* (1996) at the University of Western Ontario (R=100,000), the Hobby-Eberly Telescope High Resolution Spectrograph (HRS; R=120,000), and the NSO's solar-stellar spectrograph (R=120,000; Povich *et al.* 2001). The cross-dispersed echelle spectrometer on the 2.7-m telescope at McDonald Observatory provides R=240,000, but the spectral range sampled in a single exposure is apparently limited. The Ultra-High Resolution Facility (UHRF) at AAO provides R=300,000, but only for a few Angstroms of spectrum at a time. A multiple-pass Fabry-Perot etalon (FPE) interferometer, a double-pass echelle spectrograph with a slit in an intermediate focal plane, and a Fourier transform spectrometer (FTS) can provide the high resolving power, stable, symmetrical line spread function, and low wings.

Avoiding the Effects of Convection:

As an alternative to the exacting analysis of line bisectors, we also proposed a way of observing the RV of stars that minimizes the effects of stellar activity cycles. We made progress toward this goal in the 1990s by showing that there is a way of measuring RVs that is less sensitive than conventional methods to modulation by convection in stellar photospheres (McMillan *et al.* 1993, 1994). This capability would make RVs a more robust and comprehensive tool for the detection and analysis of orbital motion of long-period extrasolar planets, without the high resolving power needed to analyze the shapes of line bisectors. The use of lower resolving power would permit smaller telescopes to be used, thereby making more observing time available and improving the time sampling of the RV series.

Consider how to measure RVs without being confused by the effects of changing convection. The cores and steep flanks of the lines remain comparatively stationary in wavelength because they are formed in the gas at the top of the convective trajectory, while the wings that are formed at greater depth in the photosphere suffer the most from this magnetic modulation of gas velocities. Dravins (1985) recommended the exclusive use of the steep flanks of photospheric absorption lines to minimize the effects of convection on apparent RV. The relative contributions to the line profiles by rising and falling masses of gas depend on wavelength according to the properties of the continuum opacity. In violet light, the luminous contrast between the "hot", rising granules and the "cool", descending intergranular lanes is much greater because brightness varies exponentially with temperature on the short wavelength side of the Planck curve, while on the red side the brightness varies only linearly with temperature (Zirin 1988). Greater granular contrast means the line profiles are more dominated by the rising gases, providing less leverage for changing the asymmetry of the lines. An additional advantage of the violet is that photospheric lines are formed over a narrower range of depths (Altrock *et al.* 1975) and where the temperature and turbulent velocity vary comparatively little with height (Vernazza *et al.* 1973).

As mentioned above, the relative stability of the steep flanks of violet lines against convective modulation was demonstrated by McMillan *et al.* (1993, 1994) as part of a search for extrasolar planets. Their observations were made at a resolving power of 76,000, so it is not necessary to have extravagantly high resolving power to avoid convective modulation. The significance of those demonstrations has been acknowledged by experts on stellar atmospheres (*e.g.* Saar and Donahue 1997) who cited that work.

Butler *et al.* (1996), Cochran and Hatzes (1994), Cumming *et al.* (1999), Marcy *et al.* (2000), Vogt *et al.* (2000), and other discoverers of apparently low-mass companions orbiting stars measure RVs to an accuracy of 3 ms^{-1} by passing the starlight through a cell containing gaseous iodine. The rich spectrum of iodine provides a stable reference of Doppler shift to compare with the lines in the stellar spectra. However, the iodine absorption spectrum is usable only for wavelengths between 5000 and 6200 A, thus missing the advantage of high granular contrast on the short wavelength side of the black body curve. Furthermore, to reach an RV accuracy of ±3 ms^{-1} they use the whole profile of each line, thus maximizing the possibility that changes in convection could induce an apparent variation of RV.

IMPLEMENTATIONS

Fabry-Perot Etalon Interferometer:

With adequate telescope aperture and integration time, a Fabry-Perot etalon (FPE) can provide an extremely high R with relatively small optics (Vaughan 1989). Resolving powers exceeding our requirements have been achieved with FPEs as early as the original one by Perot and Fabry (1899), which Vaughan (1989) points out had $R=10^6$. An FPE scanning whole line profiles can also provide the high contrast, low wings, and stable, symmetrical line spread function required to analyze the shapes of line bisectors. We experimented with this concept in a way that had the potential for adequate telescope time and photon flux: observing parasitically through another instrument on a 10-m telescope.

A classical narrow-field *astrometric* search for planetary systems needs a large telescope on a mountaintop because the large aperture and high altitude allow the central target star and all the reference stars in the astrometric field to be observed through the same air column. Smaller telescopes need larger fields of view to sample enough reference stars, so with those this advantage cannot be attained. Gatewood has been conducting high-precision astrometry at the Allegheny Observatory (Gatewood 1987) and has found evidence for two planets orbiting the nearby star Lalande 21185 (Gatewood 1996). He obtained time at the Keck Observatory in 1997 to experiment with more sensitive astrometry.

To get enough light for R=300,000, we concurrently experimented with a new way of observing the radial velocities (RVs) of nearby stars. This was inspired by my realization that *astrometric* observations of nearby stars, while integrating on the faint reference star fields, must necessarily reject as much as 90% of the light of the target star in the center of the field in order to avoid detector saturation. In the case of Gatewood's (1987) Multichannel Astrometric Photometer (MAP) at the Allegheny Observatory, the light from each star in the field is delivered away from the focal plane by a separate optical fiber. The required attenuation of the light from the central star is accomplished at the output end of the target star's fiber. This ratio is typically 10% for astrometry and 90% rejected for most of Gatewood's astrometric targets, so he agreed to let us use the rejected light for simultaneous spectroscopy. Our combined instruments were collectively referred to as the MAPS: Multichannel Astrometric Photometer with Spectrograph (Gatewood *et al.* 1997).

We refocused the light reflected by the target star's beamsplitter into a second optical fiber as shown by Fig. 2 of Gatewood *et al.* (1997), the output of which was the entrance aperture to our instrument. Since the image scrambling by an optical fiber has always been a fundamental part of our technique for accurate measurement of RVs (McMillan *et al.* 1988), and the FPE can intrinsically provide high resolving power with a larger entrance aperture (fiber output) than that with a grating spectrograph, our technique was naturally suited to this mode of "symbiotic" observing.

The instrument we built in 1997 is shown schematically in Fig. 7 of Gatewood *et al.* (1997). The interferometer part consisted of the fiber output termination and its mount, the collimating lens, the etalon, its tilt mechanism, and a vibration-damped surface inside a temperature-controlled box on the table. The spectrograph was merely used to separate the interference orders and distribute them on a CCD. Wavelength and RV information would be derived from knowledge of the thickness of the etalon and its tilt, not the placement or resolution of the spectrum on the

CCD. The FPE interferometer with the order-separating spectrograph would provide high stability of both the wavelength scale and the wavelength broadening function. The latter would be symmetric and insensitive to focus, alignment of the spectrograph, non-flatness of the CCD, or imperfect charge transfer efficiency of the CCD. CCD pixel position would not be mapped into RVs, and many CCD pixels would be integrated into each flux measurement (McMillan *et al.* 1985, 1986, 1990, 1993, 1994). None of these characteristics are provided by absorption-cells.

We had observing runs with the MAPS on the Keck II Telescope in 1997 to experiment with the concept of symbiotic observing. Due to the late arrival of our funds in 1997, an FPE interferometer was not available, but the spectrographic part of the configuration was ready for tests of throughput. The performance with an FPE added to this system could be extrapolated from these tests.

We planned our observing with a healthy respect for the physical stress of setting up and conducting a scientific experiment in the oxygen-deprived conditions of Mauna Kea. We tested the spectrograph and optical fiber at LPL on starlight before shipment, allowing us to develop our observing procedures in the comfort of our own lab. I made two trips to Mauna Kea with Gatewood in advance of the spectroscopy run. On the first trip Gatewood and I simply conferred with Keck personnel, visited the site and took plenty of photos and video of the areas in the Keck II building we would be using. On the second trip I helped Gatewood and his personnel observe with the astrometric instrument without the spectrograph. I saw how our operations could mesh with theirs with minimal interference and to what extent Keck personnel were available to assist. We then shipped all our equipment and tools weeks in advance of the first spectroscopic run to permit Keck personnel plenty of time to truck our crates to the summit. To minimize the burden on Keck personnel and resources we rented our own four-wheel drive vehicle to commute between the Hale Pohaku residence and the summit, and staffed each of our spectroscopic observing runs with three people from our group. We checked into the residence about ten days in advance of the first observing night, so as to get acclimated to the summit conditions while gradually unpacking and setting up the experiment. These measures were quite expensive but would have been worthwhile if it had turned out we could have left our instrument set up between observing runs (see below). We brought all our own computers, accessories, tools, materials and spare parts to make our daily operations as self-sufficient as possible. A thermoelectrically cooled CCD was used so we would not have to rely on a supply of liquid nitrogen from Keck personnel.

We enjoyed hospitality and cooperation from the summit staff of the Keck Observatory, who enthusiastically performed those tasks that we were not authorized to do, *e.g.*, making ethernet connections, transporting crates, etc. Our equipment was transported from our shipping destination (Keck Headquarters in Waimea) to the summit well in advance of our observing run, and was handled with care. A long fiber of large diameter was pulled by Keck personnel through the Keck II elevation cable wrap from the straight Cassegrain focus to the only possible location for the spectrograph table that we found out at a late date that we were allowed to use: the basement. This location was much farther away from the telescope focus than we had assumed we could use when we wrote the original proposal in 1996, so the fiber was much longer than we would have liked. Subsequently that basement area was completely occupied by the beam-combining optics of the Keck interferometer, but by that time we would have relocated our instrument to the Cassegrain focus anyway.

All our spectrographic equipment was functional well in advance of the first night and operated reliably on all nights scheduled. Spectra of several of Gatewood's brighter targets were obtained. Extrapolation of those results to that expected if an FPE were added to the instrument indicated that the experiment would have worked at the Keck II telescope and that there was considerable room for improvement in throughput if a compact spectrograph could have been built and placed in proximity to Gatewood's instrument, at the end of a short optical fiber.

In 1998 it became unfeasible to operate the MAPS at the Keck Observatory because the Observatory Director decreed that all visitors' instruments would have to be removed from the summit at the end of every observing run. This requirement is fundamentally incompatible with the maintenance of a long-term stable metric with delicate optical equipment. It is also difficult to understand the rationale for it, in view of the considerable effort required of Observatory personnel to transport freight to and from the summit. Besides, we wouldn't have had the time, funds, or motivation to set up our spectrograph "from scratch" out of crates on every observing run. Instead, the MAPS could have been adapted to the 6.5-m MMT on Mt. Hopkins in Arizona. The MMT site frequently has subarcsecond seeing and observing there would be more economical. In this scenario, Gatewood's instrument would have been modified to attach to the MMT and our proposed portable spectrograph would have been operated there concurrently.

We began designing a compact spectrograph that could be used with a small FPE interferometer in close proximity to the MAPS at the cassegrain focal plane of a large telescope such as the MMT. This design drew upon the "channel spectra" concept for the use of FPEs for high resolution spectroscopy in balloon payloads (Bates *et al.* 1978, 1979; Vaughan 1989). In this application of an FPE, cross-dispersion by a second grating is not used because the coordinate orthogonal to the dispersion is needed to represent the fractional interference order along the image of a slit ("channel") formed in our case by a linear array of fibers. This provides extremely high dispersion along the channels, which are images of the slit in sequential orders of constructive transmission through the FPE. A large diameter bundle of fibers is compatible with the magnified image scale at large telescopes; said bundle being reshaped along its length into a linear array to simulate the input slit. We already own this bundle. The "channel spectra" approach would also obviate the need for any moving parts to tilt-tune the etalons - an advantage important for compact payloads suspended from a balloon or the Cassegrain focus of a telescope. Prismatic dispersion is advantageous because it partially offsets the strong dependence of FPE free spectral range (FSR) with wavelength, keeping the separation between the interference orders more uniform in terms of CCD pixels. Two FPEs would be used: the first in double-pass in a separate fiber-fed module, the second between the collimator and the first prism. The FSR of the second FPE is incommensurate with that of the first, to increase the net FSR of the two

FPEs to about 7 Angstroms, an interval the prism spectrograph can resolve. We drew upon our existing inventory of optics, detectors, and fibers to minimize the estimated cost of this unit; we were especially fortunate to have the first FPE and all three prisms of highly dispersive glass. This instrument was not completed because the mFTS (below) appeared to be more competitive.

Multichannel Fourier Transform Spectrometer:

As an alternative to the FPE, we then explored the merits of a Fourier Transform Spectrometer (FTS). The high resolving power and intrinsically symmetrical instrumental line spread function of the FPE that made it especially suitable for studying this problem is shared by the FTS; both are based on interference between two flat plates rather than on diffraction by the many grooves of a grating. However, an FTS is much more efficient with photons than an FPE.

At a meeting I met a group from the US Naval Observatory that was seeking a collaborator familiar with RVs who also had access to a large telescope. Dr. Arsen Hajian (USNO Washington), who is usually in the business of imaging interferometry, has developed a new type of multichannel Michelson Fourier Transform Spectrometer (mFTS). This instrument can revolutionize the measurement of Doppler shifts of stars because it will be sensitive to velocity changes as small as 0.3 m s^{-1}, ten times smaller than the precision achieved by Butler et al. (1996) (Nordgren and Hajian 1999). They wanted to apply their mFTS to current topics in Doppler shift research, but said they have neither the scientific background in that field, nor access to large telescope time. The combination of their instrument with our fiber optic feed and knowhow in measuring Doppler shift seemed ideal, so I responded to their request. They agreed to collaborate with me.

Development of the mFTS (USNO 2002) has progressed with my participation. I have contributed especially my knowhow in fiber optics, which are essential to feed light from the focal point of a telescope to a bench-mounted instrument such as this. I also contributed the idea to use the mFTS to make measurements of RVs in a way that should be insensitive to the effects on spectral lines caused by stellar activity ("spot") cycles. Contrary to the now commonly-used iodine cell for Doppler shift calibration, the closed-loop stabilization of the mFTS provided by laser metrology will allow measurements of Doppler shift in violet light (400-450 nm) where the line profiles are more stable with time (McMillan *et al.* 1993, 1994). USNO is testing their instrument by observing bright stars with a small rooftop telescope and integrated-disk sunlight in the daytime with the unassisted fiber. In preparation for future calibration by sunlight reflected from the Moon at night, I wrote software to predict the Doppler shift of sunlight reflected from the lunar crater Mösting A to an accuracy of 1 ms^{-1}.

OTHER EFFORTS

Line Lists: I compiled lists of spectral lines from hollow-cathode emission lamps for the purpose of calibrating the wavelength scale of an FPE and/or for checking the wavelength scale of an mFTS. I also used the literature on high resolution spectroscopy of the sun and stars to compile a list of unblended moderate-strength photospheric absorption lines that have been used by experts to study line bisectors. These lists have been forwarded to Dr. Arsen Hajian of USNO as competitive assets for the mFTS project.

Stellar Atmosphere Software: I procured commercial software to compute model atmospheres of stars for the purpose of verifying the explanation by Zirin (1988) of the advantage of measuring RVs in violet light.

Spacewatch 1.8-m Telescope: Observing time with this telescope centered on full Moon may be available for Doppler shift spectroscopy because it was built partly for that purpose. This grant partially supported the successful effort to make that telescope operational.

Fabry-Perot Spectroscopy of Mercury's Atmosphere: My expertise and our Project assets were tapped by Dr. Ann Sprague and Regents Prof. Don Hunten to do fiber-optic-fed FPE spectroscopy of Mercury. Their objective was to see whether emission lines from its rarified atmosphere showed high velocity wings. Two observing runs at the University of Arizona Observatories' Catalina Station 1.55-m telescope were unsuccessful due to bad weather and low efficiency of the Fabry-Perot system brought out by Dr. Robert Kerr of Boston University. Hunten made an independent measurement of the throughput of the fiber I provided and found its performance satisfactory and therefore not at fault. Participating in this experiment exposed me to the operation of three FPEs in series that provided R=600,000, twice what our experiment would require. I learned that it is vital to be able to inspect the transmission profile from each of the FPEs alone, with the science detector, without removing or re-installing the other FPEs. Kerr's setup did not permit this, but by coupling the output of one FPE through fiber optics to the next FPE, one would be able to accomplish this by switching fiber connectors.

Astrometric Support: In support of Gatewood's program of astrometry during our collaboration with him, a large number of direct images of his planet-search target fields were obtained by Spacewatch observers. Gatewood used these images to select reference stars around his targets.

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