Absence of a planetary signature in the spectra of the star 51 Pegasi

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51 Pegasi, one of many nearby Sun-like stars, was undistinguished until the recent detections of apparent variations in its radial velocity, which have been attributed to reflex motion caused by a planetary companion[1,2]. The velocity variation inferred from variations in the spectral lines of 51 Peg has an amplitude of 56–59 m s^{-1} and a period of 4.23 days, implying a planet of at least half the mass of Jupiter moving in an embarrassingly small orbit of 0.05 astronomical units. But the techniques currently used to identify these exceedingly small radial velocity variations do not allow for the possibility that changes of comparable size might be occurring in the intrinsic shapes of the spectral lines; such variations are expected when a star pulsates or has spots on its surface, and could be mistaken for radial velocity variations. Here I present high-spectral-resolution observations of 51 Peg that show that its spectral lines exhibit intrinsic shape variations with a period of 4.23 days, and an amplitude comparable to that previously attributed[1,2] to radial velocity variations. As the presence of a planet will not influence the shapes of spectral lines, these variations are likely to reflect a hitherto unknown mode of stellar oscillation. The presence of a planet is not required to explain the data.

As part of a long-term study of magnetic-cycle-type variations in cool stars[3,4], observations of 51 Peg have been collected for a number of years at the University of Western Ontario using a coudé spectrograph[5] having a resolving power of ~100,000. This Letter is based on data from 39 exposures taken between 1989 and 1996.

Two types of information were extracted from the spectra. First, the asymmetry of the 6,252.57-Å Fe I spectral line was measured. Spectral lines in cool stars are asymmetric primarily because of granulation on their surfaces[6–8]. This asymmetry has been specified using The line bisector, that is, the locus of points bisecting horizontal line segments running between the sides of the spectral line. The line bisectors for cool stars have a somewhat distorted 'C' shape, the details of which vary from one spectral line to the next. Systematic changes in bisectors occur with effective temperature and luminosity of the star[9]. Non-radial pulsation[10] and rotational modulation arising from a non-uniform surface[11] can cause temporal variations in the asymmetry. Figure 1 illustrates the 39-exposure average line bisector for 51 Peg. The velocity span, measured between bisector points at 0.50 and 0.90 of the continuum (shown by horizontal arrows Fig. 1) is a simple measure of the overall slope of the bisector. The changes in the line profiles are subtle and not at all apparent from casual inspection of the spectra; the spectral liens are ~15,000 m s^{-1} wide, against which the bisector span (~50 m s^{-1}) and its variations are minuscule.

The second parameter measured is the ratio of the central depths of two lines having different sensitivity to Doppler broadening and to temperature, 6,251.83-Å V I to 6,252.57-A Fe I. Radial velocities, in the sense of displacement of the whole spectral line, are not available from these data because no absolute velocity reference frame is recorded during the observations.

Variations occur in both the line bisector and the line-depth ratio. Although the dates of most exposures are too far apart to allow identification of periods as short as a few days, we can use the orbital parameters obtained by Mayor and Queloz[1] (a period of 4.2293 d and an epoch of Julian day 2449797.773) to compute a phase diagram for the spectroscopic data. The phase was computed for each exposure, and individual values of velocity span and line-depth ratio were averaged in phase bins according to the natural grouping of the points. The results are shown in Fig. 2, where a periodic signal is apparent. The periodic variation is seen in the contiguous nightly data and all the 1996 data (top panel), in data over the full 1989–96 interval (second panel), and in the phase-mean plots of velocity span and line-depth ratio: the spectral lines of 51 Peg have intrinsic variations with a period of 4.23 d.

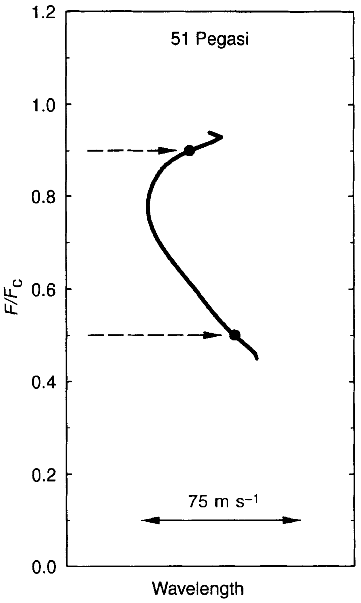

Figure 1 The average of 39 exposures of the line bisector of Fe I 6,253 Å. The plot of F/F_c, flux normalized to the continuum, against wavelength displays the typical 'C' shape induced by granulation on the surface of the star. Hot convective cells rise, giving to their light a net Doppler shift to the blue (integrated over the hemisphere of the star facing us), while cooled material returns downward, giving a net Doppler shift to the red. As the fraction of light coming from the hot material is substantially larger than the light from the cooled material, the combined effect is an asymmetrical broadening of the spectral lines. The wavelength difference, expressed in velocity units, between the two indicated points is the velocity span used to parametrize the cyclic variations in the upper panels of Fig. 2.

The velocity span varies by ~±45 m s^{-1}, a value comparable to the radial-velocity amplitude found by Mayor and Queloz based on many spectral lines. Because our observations do not tell us if the top or the bottom (or both) of the bisector is moving relative to an absolute frame, the physical phase in Fig. 2 is ambiguous by 180°, and so the near anti-phase with the radial velocities has no immediate significance. One should not even conclude that velocity-span variations translate directly into radial velocity variations. More than likely, there is also a shift of the whole line occurring along with the change in bisector shape, and although this cannot be ascertained directly from my spectroscopic data, such a shift could be the primary effect producing the radial velocity variations.

The physical interpretation of the variation in line-depth ratio is likely to be equally complex, especially if non-radial pulsation is involved. Although line-depth ratios have been used as temperature indicators in previous investigations[12–14], it would be foolhardy to make the same interpretation here. Oscillatory upheavals in the star's atmosphere could re-shape spectral lines through their Doppler shifts and altered radiation transfer. The lack of brightness variation[15,16], provides a strong constraint on

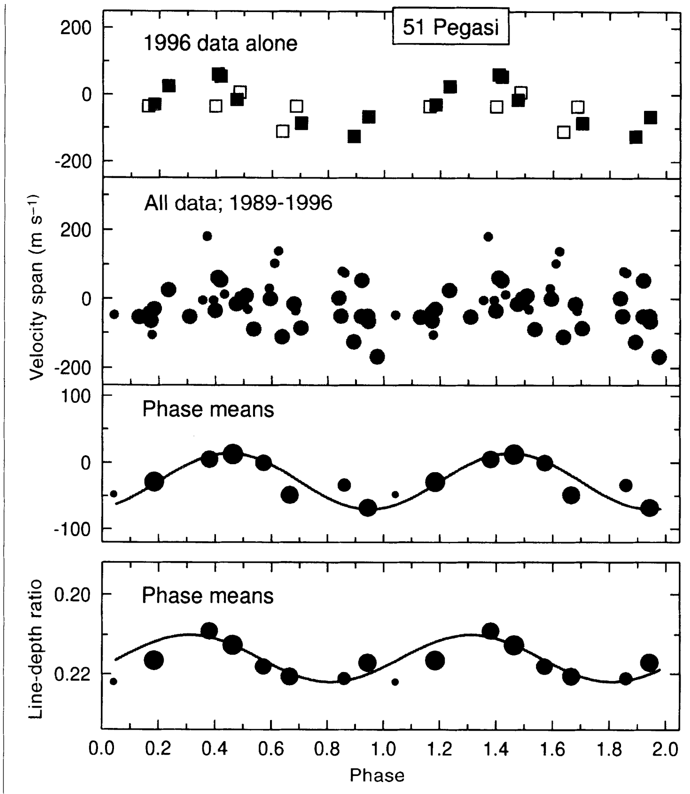

Figure 2 The three upper panels show the velocity span of 6,252.57 Fe I as a function of phase according to the Mayor and Queloz[1] ephemeris (period of 4.2293 d). The top panel shows just the 1996 data, with contiguous points in time shown by the filled symbols. In the second and third panels, larger symbols are used for higher signal-to-noise ratios of the exposures and their means. In the bottom panel, the ratio of the central depths of the V I to the Fe I line is plotted. The cosine curves have the 4.23-d period; the amplitude for the velocity-span curve is 44 m s^{-1}.

modelling these effects.

Regardless of the details of their final interpretation, the 4.23-d spectroscopic variations of 51 Peg are intrinsic to the star; reflex motion of an orbiting planet does not alter the shapes of line profiles.

It is important to realize that high spectral resolving power, >100,000, and high signal-to-noise ratios are needed to see the asymmetries of spectral lines[8,17]. Radial velocity investigations generally lack this essential ingredient. For example, Mayor and Queloz[1] used a spectral resolution of about half this amount, well below what is needed. At this low a resolving power, the asymmetries of spectral lines virtually disappear. In the one other high-resolution study that has been done, there were simply too few data to be certain of any profile variations[18].

Non-radial pulsations can produce variations in spectral line bisectors that are similar to those seen for 51 Peg[10], although a period of 4.23 d is somewhat larger than one might have guessed based on the solar 5-minute p-mode oscillation. On the other hand, gravity-mode oscillations can have much longer periods[19]. Some independent evidence points toward 51 Peg being larger than a normal dwarf star, and this too would give longer periods[15,16,20,21]. Evidence for low-amplitude long-period pulsations in evolved stars has been seen by several investigators including Walker *et al.*[22] The results of non-radial oscillation modelling of these data will be reported elsewhere.

Claims of several other planets outside our Solar System have been made based on this same reflex-motion argument[23–27]. Periods of radial-velocity variation range from a few days (for example, τ Bootis, υ Andromedae, ρ^1 Cancri and 51 Peg, through a few weeks and on to a few years for 47 Ursae Majoris and 16 Cygni B. Given the spectroscopic results presented here, non-radial oscillations and possibly rotational modulation are serious contenders for explaining the radial-velocity variations up to a few weeks in length. Rotational modulation becomes an unlikely explanation when the period exceed several tens of days, the normal range for stellar rotation. Non-radial oscillation may not be a viable explanation for periods exceeding a few days, as such long periods are not expected, and because integration of the radial velocity curves imply unreasonably large motion of the stellar surface. However, these kinds of speculations cannot replace high-resolution spectroscopic observations, and they have yet to be done.

Although at this stage, the cause of the spectral line variations in 51 Peg are not fully understood, the chance of their being caused by a planet is vanishingly small. The only hope now for the planet hypothesis, as applied to 51 Peg, is to claim that the spectral variations are somehow driven by the presence of a planet. To make such a claim is actually self-defeating because the intrinsic spectral-line variations will account for most or all of the apparent radial velocity variation upon which the original hypothesis was based. So even if such a claim were to prove true, the planet would be very different from the one originally proposed to explain the radial-velocity variations. On the positive side, it seems likely that the variations shown by 51 Peg will give us an exciting new window into the subtle behaviour of cool stars like our Sun. ☐

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