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EVIDENCE FOR PERIODIC RADIAL VELOCITY VARIATIONS IN ARCTURUS

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ABSTRACT

We report evidence for periodic radial velocity variations in Arcturus; the most likely period and amplitude for these variations are 1.842 ± 0.005 days and 160 ± 10 m s^{-1}, respectively. Observations of Pollux taken on many of the same nights show no significant power on time scales between 2 days and 2 months; the nightly accuracy of these data is ±18 m s^{-1}, which is indicative of our long-term instrumental accuracy and about one-third of the standard deviation of the Arcturus data. Epoch-folding 31 nights of Arcturus data taken between 1985 December 21 and 1986 March 31 reveals a "sawtooth" phase diagram. Two physical mechanisms are discussed briefly as potential causes of this variation.

Subject headings: stars: atmospheres — stars: individual (α Bootis) — stars: late-type — stars: pulsation

I. INTRODUCTION

An intense, long-term observing program, which began in 1985 September at the University of Arizona, has been designed to detect planets orbiting stars by measuring the periodic variations such companions induce in the stellar Doppler shifts. Although this program includes primarily solar-like stars, during the first year of our search we concentrated on bright K giants. Our rationale for this was twofold. First, since little is known about the variability of stars in this part of the H-R diagram, we were searching for velocity fluctuations with periods between a few months and a few minutes (periods less than 1 day are to be published separately) with a precision of several m s^{-1}. Second, these stars provide a convenient evaluation of the performance of our instrument for the planet detection program on a time scale of many months. They are ideal calibrators both because they have a high density of sharp spectral lines in the violet and because there are many bright stars available to our telescope.

Many studies of the radial velocity of Arcturus have been published which quote night-to-night errors significantly smaller than those obtained by using "conventional" techniques (see Adams 1941, Beavers *et al.* 1979, Bopp and Edmonds 1970, Griffin and Griffin 1973, and Petrie and Fletcher 1967). These data, however, are too noisy to contribute to the present investigation. There are a few groups who have claimed night-to-night errors comparable to ours and who have also observed Arcturus. Campbell, Irwin, and Walker (1982) have been observing Arcturus with a precision radial velocity spectrometer calibrated with a hydrogen fluoride absorption cell. M. A. Smith (1982) reported three contiguous nights of observations on Arcturus which are given on the same velocity scale, although the intent was to search for oscillations having periods of a few hours. His method uses telluric lines as calibrators. Another group, whose technique is described by Hall and Hinkle (1981), has accumulated observations (near 2 μm) for several years using an FTS with a nitrous oxide absorption cell. Although this group has not yet published any results, data reduction is currently underway (K. H. Hinkle 1986, private communication).

II. INSTRUMENT AND CALIBRATION

Our Doppler accelerometer is an interferometrically calibrated spectrometer. A single optical fiber feeds the light from the telescope focal plane to the spectrometer entrance aperture. Wavelength calibration is imposed on the starlight by a tilt-tunable Fabry-Perot interferometer used in transmission which is in turn calibrated by observing argon and iron emission lines from a hollow cathode lamp. The scrambling of incident light by the fiber and the stability of wavelength calibration by the etalon provide immunity to the systematic errors (Griffin and Griffin 1973) that historically have plagued radial velocity measurements with conventional spectrographs.

To separate spatially the orders of constructive interference transmitted through the etalon, the spectrum is dispersed by an echelle grating crossed with a conventional plane diffraction grating. The two-dimensional spectrum is focused on a charge-coupled device (CCD) used as a detector. From 10 echelle diffraction orders in the vicinity of 4250–4750 Å about 300 points on the profile of the stellar spectrum are sampled by successive orders of interferometric transmission through the etalon. At 4300 Å each interference order is 47 mÅ wide, and the sample points are 640 mÅ apart, causing distinct, widely spaced monochromatic images of the entrance aperture to be formed in the focal plane of the camera.

The Fabry-Perot etalon defines the absolute wavelengths of the sample points in the laboratory frame. Changes in the stellar Doppler shift, and thus the stellar wavelengths, modify the relative intensities of these images, in proportion to the slope of the spectral profile at each point sampled. In the violet spectrum of a K giant star, approximately 25% of the orders are sensitive to changes of Doppler shift, by virtue of their locations on the steep slopes of line profiles.

More detailed descriptions, illustrations, and quantitative parameters of the detector and optics have been given by Frecker *et al.* (1984) and McMillan *et al.* (1985). McMillan *et al.* (1986) describe the methods of calibration, data reduction, and determinations of typical errors of measurement. The rationale behind our choice of spectral region is given by Merline (1985).

The interferometer is calibrated to better than two parts in 100 million on an absolute scale with an iron-argon emission source; this corresponds to ± 6 m s^{-1} in radial velocity. All error estimates in this *Letter* correspond to the standard deviation *per* sample. The instrumental corrections determined by the calibration procedure and applied to the data have an average absolute value of 18 m s^{-1} with a maximum range over the 4 months of ± 37 m s^{-1}. The internal repeatability of observations of the differential radial velocity of Arcturus is ± 4 m s^{-1} for each exposure of 3–4 minutes with our 0.91 m telescope. This internal error is dominated by readout noise from the CCD detector array. The external repeatability (night-to-night differential accuracy) of bright stars is usually ± 20 m s^{-1} or better. This error is dominated by uncertainties in the temporal variations of the tuning parameters of the interferometer and in applying interferometric calibrations to stellar observations.

III. OBSERVATIONS

Arcturus was observed on 31 nights during the bright lunar phases between 1985 December 21 and 1986 March 31 UT inclusive, a span of 100 days, with the 0.91 m telescope of the Steward Observatory on Kitt Peak. Pollux was observed on 18 nights between 1986 January 22 and March 31 UT, a span of 68 days, using similar procedures. On nights when more than 10 observations were obtained, the average reduces the short-term internal random errors to at most one-tenth of the systematic errors expected from the absolute calibrations of the interferometer. The nightly averages of velocities and the numbers of observations from which the averages were derived are listed in Table 1.

Since Pollux is 1 mag fainter than Arcturus in violet light, the exposure times were proportionately longer to obtain the same ratio of photometric signal-to-noise. The great similarity of color, spectral type, and luminosity class of these two stars allowed us to use the same spectral region and detector areas for both stars.

The time dependences of the radial velocities of Arcturus and Pollux referred to arbitrary zero points are illustrated as functions of day of year in Figure 1. The four groupings of the data in time correspond to our observing runs in 1985 December and 1986 January, February, and March. The scatter of the observations of Pollux about their mean value is ± 18 m s^{-1} (standard deviation); we interpret this as an upper limit to the night-to-night error intrinsic to our technique on bright K giant stars. The standard deviation of the Arcturus data (Table 1) is ± 62 m s^{-1}; there is only an infinitesimal probability of obtaining a set of 31 points with this variance from a parent distribution having a standard deviation of ± 18 m s^{-1}. Therefore, the variations must be due to environmental factors, some instrumental effect, the reduction technique, or the star itself. We discuss and reject the nonastrophysical possibilities in order, bearing in mind that such explanations must perturb only the Arcturus data.

TABLE 1

DIFFERENTIAL RADIAL VELOCITIES OF ARCTURUS

DOY[a]	n[b]	V (m s^{-1})
−9.46	10	−37
−8.47	10	−35
−7.44	12	−29
−1.45	5	−60
−0.42	13	−106
22.51	70	−18
23.55	32	−84
24.53	22	−20
25.57	14	−82
26.52	8	23
30.57	3	−110
53.45	37	−59
54.55	29	−143
55.54	30	−78
56.49	3	−130
57.48	2	−58
58.48	2	−109
59.41	4	27
60.43	38	−206
61.47	35	−58
78.40	59	−151
79.41	64	−9
81.44	40	−11
82.46	41	−76
83.52	16	34
84.46	34	−68
85.45	56	−1 (Ref)[c]
86.39	77	−53
87.52	7	24
89.46	33	−129
90.39	15	64

NOTE.—All observations have an uncertainty of ± 18 m s^{-1}.

[a] 1986 day of year = Julian Date − 2,446,430.5.

[b] Number of observations used in calculating the average nightly velocity V.

[c] Night containing the zero-velocity reference observation.

During the 4 month observing season discussed in this *Letter*, there was a wide variety of environmental conditions. We have examined correlations of the Arcturus velocity data with the angular distance from the Moon, lunar phase, the degree of cloudiness, hour angle, time of day, seeing conditions, guiding/tracking conditions, the observer, ambient temperature, ambient humidity, and length of observing session each night. Similar correlations also were done using the Pollux data, which should be more sensitive due to the absence of a strong intrinsic velocity variation. There is some evidence for a very weak dependence on hour angle under the most severe temperature, humidity, guiding, and cloud conditions. This applies to only about 5% of our data and cannot account for the observed variations in Arcturus. No systematic shifts are seen between different observers.

Due to the small tolerances that must be maintained to measure minute changes in radial velocity, there are many potential sources of instrumental uncertainty and error. Some of these are different tilt regimes, the periodicity of the

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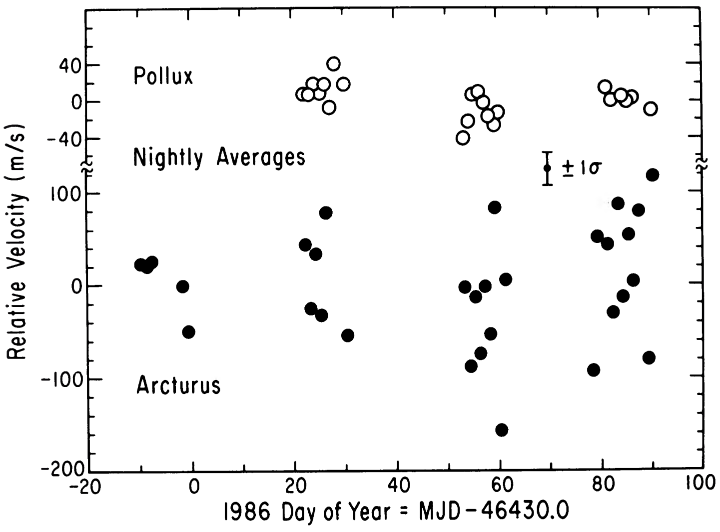

FIG. 1.—Radial velocities of Arcturus and Pollux. The abscissa is 1986 day of year = Julian Date − 2,446,430.5. The velocity scale of each star is set to zero at the mean value. A typical error bar is indicated.

rotating micrometer spindle that tilts the etalon, and variations of temperature and pressure within the interferometer. Temperatures and pressures at various critical points within the instrument are frequently monitored during an observing run; they show no correlation with velocity. There is some hint of a correlation between the azimuth angle of the micrometer and the velocity of Pollux but the semiamplitude of the variation is less than 5 m s^{-1} and is at the limit of detection. The two stars are observed using substantially the same Fabry-Perot orders and are tracked, to compensate for Earth motions, by tilting the etalon over the same angular range. Most of these error sources apply equally to the two stars and cannot be considered to produce the observed variations of Arcturus. Furthermore, these error sources have been well documented over many years of calibration and laboratory testing, as well as during months of stellar test observations.

Further correlations were performed on parameters which could be indicative of problems with the data reduction method including the amount of calibration correction applied to the stellar data, the position of the spectrum on the detector, the exposure level, the signal count rate, the exposure time, the number of observations per night, and the velocity corrections applied to reduce the data to the barycenter of the solar system. The only convincing evidence of a correlation is that there appears to be a weak relationship between the location of the spectrum on the detector and the Pollux velocities. This effect is too small to account for the Arcturus variations, and such a correlation does not appear in the Arcturus data. The same reduction software was used for both stars in the same manner, although the stars are reduced independently.

IV. SEARCH FOR PERIODICITY

A periodogram analysis (see Fig. 2) based on the formulation of Scargle (1982) and Horne and Baliunas (1986) yields periods of 1.842 and 2.183 days. The uncertainty associated with these periods, computed from equation (14) of the Horne and Baliunas paper, is estimated to be ±0.005 days. They also suggest that an uneven data spacing will not degrade this resolution. The periodogram has such high sensitivity because the length of the data interval is approximately 50 cycles, and the radial velocity oscillation "curve" has a sharp edge. Since the two peaks are aliased about the Nyquist frequency at 0.5 inverse days, they are equally significant in the periodogram analysis.

A detailed analysis, as suggested in Horne and Baliunas, has been performed to assess the significance, or false alarm probability, of the feature labeled $P = 2.18$ in Figure 2. Using the same unevenly spaced sampling times given in Table 1, random data were generated having the same variance as the Arcturus data and periodograms created from these synthetic data were searched for the highest peak value. The cumulative probability distribution for peak values of the normalized power was derived and used to compute the probability for obtaining a peak of height 7.6 (see Fig. 2) from random data. The probability is less than 2%, a confidence level of 98%. The procedure has been repeated using the velocity values tabulated in Table 1, but randomly scrambled among the sampling times; the results are essentially equivalent to the random data case.

The two sidelobes on either side of the two highest peaks are a consequence of spectral leakage due to the 2 week window imposed by our observing schedule. The CLEAN algorithm (Roberts, Lehar, and Dreher 1987), a method for removing the effects of the spectral window from the power spectrum, was run on the periodogram, completely removing the secondary features in the frequency range of 0.4–0.6 per day (see Fig. 2). However, the peaks at 1.967 and 2.033 days' period do show acceptable phase diagrams; the other two sidelobes are found not to be acceptable solutions. When the data are forced into phase diagrams with periods of exactly 2 solar days and 2 sidereal days, no systematic trend or shape appears; evidently, the phenomenon is not associated with our diurnal observing cycle.

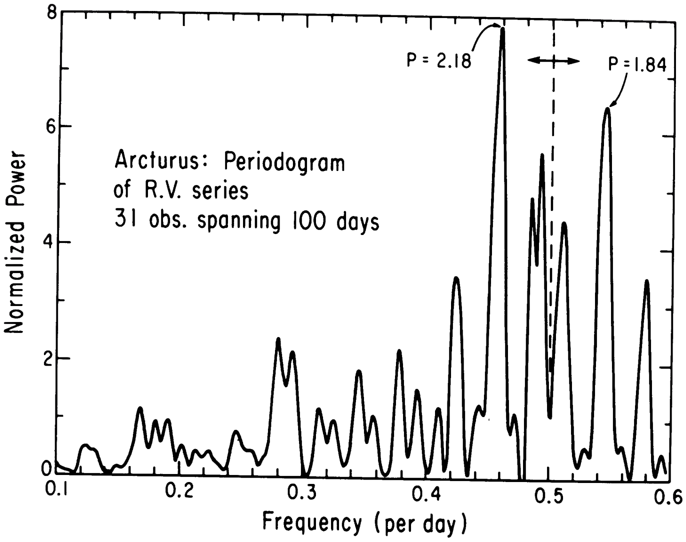

FIG. 2.—Periodogram of the Arcturus data listed in Table 1 and plotted in Fig. 1. The frequency resolution is estimated to be 0.005 inverse days; however, a smooth, interpolated curve is plotted to show clearly the shape of the power spectral window. Because the data are typically taken each day, the Nyquist frequency is 0.5 per day, and the two highest peaks shown are aliases of each other and therefore equally significant. The sidelobes on either side of these peaks are caused by the 2 week gaps in the data. Statistical tests with both scrambled and random data show that there is less than a 2% chance of obtaining peaks of this height from random data sets with the same variance as that observed.

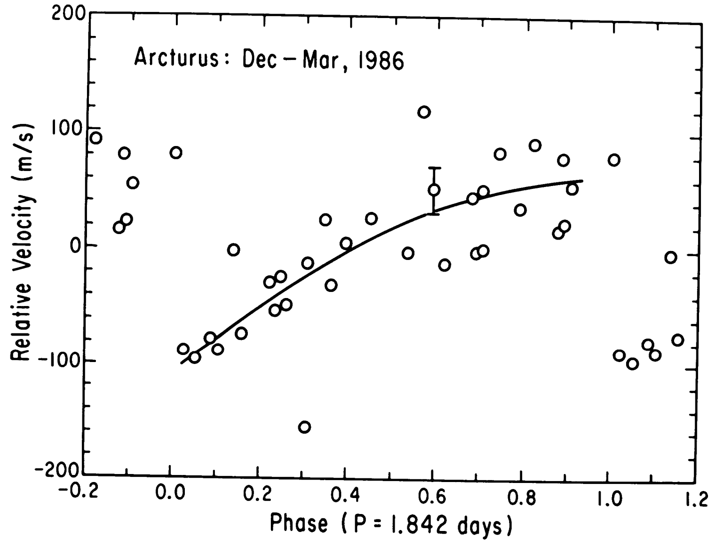

FIG. 3.—Velocity vs. pulsation phase for Arcturus. The period used in the epoch-folding procedure was 1.842 days. The solid curve is an eyeball fit to the data; the standard deviation of the residuals is nearly the same as that for the Pollux data.

The periodogram does not show any significant power for longer periods up to about 50 days. There is no evidence to suggest that Arcturus is oscillating at its fundamental radial mode frequency, which is predicted to be near 7 days (Cox, King, and Stellingwerf 1972).

The behavior of the star as displayed in Figure 1 is undersampled, so we must consider the possibility of aliasing. The period cannot be one-half the apparent one because the velocity would not alternate from night to night. Other harmonics, specifically the second and fourth with periods of about 16 and 10 hr, are formally possible; however, since long time series were obtained on many of our observing nights, the drift in velocity within a night can be used to discriminate between the possibilities. An average of the measured slopes obtained on 14 nights gives a drift of -0.4 ± 1.0 m s^{-1} hr^{-1}. This value is not consistent with either the second or fourth harmonic, which imply values of about 10 and 16 m s^{-1} hr^{-1}. The uncertainty of the nightly drift measurements is dominated by systematic errors in the estimate for the instrument drift. Because of this uncertainty, we cannot discriminate between the 2.183 day and 1.842 day periods which would drift at rates of -3.1 m s^{-1} hr^{-1} and $+3.5$ m s^{-1} hr^{-1}, respectively.

Figure 3 illustrates the "best-looking" epoch-folded phase diagram for a period of 1.842 days. The "sawtooth" curve is shown only to approximate the amplitude of the oscillation; it was not used to find this period. The standard deviation of the points about this curve is ± 21 m s^{-1}, indicating that if the "sawtooth" function were subtracted from the data only the uncertainty due to night-to-night calibration errors would remain. The amplitude of the curve is 160 m s^{-1}, 8 times the spread of points about the line.

V. DISCUSSION

Velocity variations have been suspected for Arcturus by several research groups. Campbell, Irwin, and Walker (1982) and Walker (1983) reported orally, but did not publish, data indicating that the radial velocity of Arcturus had changed over 2 days by about 100 m s^{-1}. M. A. Smith (1982) reported three contiguous nights of observations which showed velocities of about 0, -15, $+15$ m s^{-1}, the spread of which was attributed to night-to-night errors. Our own suspicions about the stability of the radial velocity of Arcturus were raised in 1984 with test data obtained with an earlier version of the same instrument used for the present investigation (McMillan *et al.* 1985). We observed a change of 127 m s^{-1} over a 1 day interval, while a 6 day interval gave no change. Kemp *et al.* (1986) analyzed a long series of polarization measurements and Ca II H and K flux measurements; they find evidence for activity on a scale of 1–5 days as well as a possible 45 day period.

On first inspection, Smith's data would appear to be inconsistent with our findings. There are at least four possible explanations for this discrepancy: (1) the amplitude of velocity variation is smaller at the wavelengths at which he observed; (2) the star was not varying when he observed it; (3) his night-to-night velocity errors, dependent on atmospheric motions and instrumental drifts, are poorly determined so that the 30 m s^{-1} change observed between his second and third nights may be consistent with the 85 m s^{-1} we would predict; (4) he happened to observe at times during the velocity cycle that had the same velocity. If the nights are phased just right, as our first three nights are, three consecutive nights can give roughly the same velocities. We conclude that Smith's data neither support nor refute our claims for periodicity.

Simple calculations have been performed to estimate the preferred period of the fundamental radial mode of pulsation and its first two harmonics. We have used the surface gravity of $\log g = 1.8 \pm 0.2$ (Bell, Edvardsson, and Gustafsson 1985), the angular diameter of $0\farcs023 \pm 0\farcs0012$ from Ayres and Johnson's (1977) reanalysis of direct angular diameter measurements, and the trigonometric parallax of $0\farcs092 \pm 0\farcs005$ (Woolley *et al.* 1970). To obtain approximate agreement with the observed period one is forced to use "1 σ" extreme values of these parameters ($\log g = 2.00$, angular diameter = 0.0219, and parallax = 0.097). A mass of 2.15 solar masses and $\log(\text{mass/radius}) = -1.053$ were calculated from these parameters and were used in the algorithms of Cox *et al.* (1972) to compute values of $\log Q$ and pulsation periods. The most relevant result is that the "2H" mode of radial oscillation would have $\log Q(2) = -1.652$ and a period of 1.82 days. Studies need to be done to determine whether such radial modes are expected to be excited or sustained, especially in the absence of the fundamental. The "Q" algorithms of Cox *et al.* refer to stars with higher envelope abundance (Y) of helium and less convection than Arcturus is expected to have. Sustained radial overtone pulsations, to our knowledge, have not been seen previously in this part of the H-R diagram.

An alternative explanation has been outlined by I. Furenlid (1986, private communication). The sawtooth "ramp," representing a deceleration of atmospheric gas, might correspond to the full cycle of upward and downward motion of convective cells. If the total number of cells visible on the stellar disk is small enough and if their motions are physically correlated, then the light integrated over the disk of the star would show a small residual amplitude of velocity oscillation. The strong limb darkening in our spectral region would tend to weight preferentially the cells nearest the center of the disk. The sharp transition of the sawtooth would correspond to the disappearance of descending cells with partially correlated motions into the underlying atmospheric layers and the (partially correlated) appearance of other rising cells. Thus no high acceleration of gas would be required to explain the sharp transition in the velocity curve. It is not known whether this statistical process would sustain phase coherence for the observed number of cycles.

Observations at other wavelengths would not necessarily be expected to show this oscillation because the lines might be formed at different levels and the limb darkening might not be as strong. In such cases, the Doppler shifts due to the various cells all over the disk would tend to average more closely to zero.

The sense of the radial velocity scale in Figure 3 is the standard convention, so the curve shape displayed corresponds to a high outward acceleration by the atmosphere of the star, followed by a more gentle deceleration. The periods greater than 2 days suggested by the periodogram yield phase diagrams with a mirror image of this sawtooth, i.e., a slow ramp downward followed by a steep rise. As mentioned above, we cannot distinguish between these two interpretations from the data alone; however, the velocity curves of variable stars with "sawtooth" profiles and the Furenlid convection mechanism both favor the sense of the lower period profile. Therefore, the peak at 2.183 days in Figure 2 is likely to be an alias of the peak at 1.842 days.

Our instrument is designed for the greatest possible sensitivity to changes of stellar Doppler shift that can be achieved with a small telescope and spectrograph. One of the assumptions made to achieve this objective is that the shapes of the line profiles do not vary with time, that is, we do not derive the radial velocity by direct inspection of the profile of a spectral line. This limitation applies to most radial velocity spectrometers which rely on some type of cross-correlation or other comparison of a large ensemble of spectral lines. Temporal stability of spectral line profiles may be an unreliable description of spectra of the integrated disks of rapidly evolving stars with tenuous, convective atmospheres and many opacity sources which depend strongly on temperature and pressure. In addition, the violet spectrum of K giants is crowded with lines and is far away from the flux maximum, making our observations more sensitive to the vertical structure and atomic physics of the atmosphere. Therefore, more observations of different types are needed before this phenomenon can be explained fully.

We owe a debt of gratitude to the memory of the late Krzysztof M. Serkowski (1930–1981), who built the original form of the instrument we now use. The detector system, telescope drive, and real-time software for same are the work of J. E. Frecker. Preparation of the fiber optic cable terminations and much of the auxiliary electronics are the work of M. L. Perry. Indispensable help was rendered by K. Denomy, L. R. Doose, R. L. James, N. A. Levenson, S. J. Marinus, R. J. McLean, S. K. Pope, J. V. Scotti, R. E. Sumner, M. Williams, and W. Z. Wisniewski. This project is supported by NASA grant NAG2-52, NSF grant AST-8403285, private and corporate donations to T. Gehrels's Spacewatch Project, and the generous allocation of telescope time and facilities by P. Strittmatter, Director of Steward Observatory. The CCD detector system, data reduction computer, and new telescope drives were funded by NASA contract NASW-3454.

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