Precise Stellar Radial Velocities
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Retrospect

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1. Introduction

What an excellent colloquium! The measurement of precise radial velocities is now firmly established in the arsenal of observational astronomy and complements the spectacular improvements in astrometric precision from space and interferometry from the ground. Announcements of candidate planets have generated a huge amount of scientific and public interest and provided NASA with copious free publicity for its Origins program. The mapping of stellar surfaces and the probing of their interior structure from nonradial pulsations must be among the most exquisite measurements in science. We have celebrated all of these achievements here. It is quite ironic and a sad reflection on priorities that so many of the most exciting contributions were from authors without permanent positions.

Let me suggest that IAU Colloquium 170 be dedicated to Buys Ballot who, in 1845, being skeptical of Doppler's (1842) explanation for the different colors of double stars, undertook an experiment with two horn players and a locomotive on the Utrecht to Amsterdam railway (Jonkman 1980). The horn players were gifted with perfect pitch, one rode on the locomotive (named Hercules, by the way) and the other stood beside the track. The one by the track noted the change in pitch (in eigths) of the horn played on the locomotive as it approached and receded, this being long before Hertz and units of frequency, and Ballot succeeded in estimating the train's speed of 18 ms^{-1} to within 2 ms^{-1}. A remarkable feat! You might quibble that the velocity of light is a million times greater than sound, but it has still taken us more than 150 years to approach this precision for stars.

The quality of the contributions to the colloquium has been so uniformly high that I omit mention of specific authors in what follows.

2. Absolute Velocities

The emphasis has been on precise radial velocities and highly accurate accelerations rather than scientific programs specifically requiring accurate radial velocities. We now have the prospect of determining accurate velocities independently of Doppler shift for nearby stars from secular accelerations measured by Hipparcos and ground-based interferometers.

The whole definition of radial velocity, in the source and the observer frames was very carefully discussed and we heard the very sensible suggestion that Commission 30 of the IAU join observational cosmologists in adopting cz as the definition of radial velocity, where $z = \Delta\lambda/\lambda$ and c is the velocity of light. We were reminded that gravitational red-shifts and those induced by granulation can amount to many hundreds of m s^{-1} for solar-type stars.

Stars are not billiard balls. The motion of their centre of mass is rarely the same as their surface. The apparent velocity of the photosphere is strongly affected by differential rotation, temperature irregularities, granulation velocity fields, and stellar oscillations. All of these effects were discussed in detail here and, when they can be isolated, each contains valuable scientific information.

In this context, the so-called Standard Velocity Stars present an important issue. These standards were established in the days of photographic spectra and wide-field objective prism radial velocity surveys. Do we still need them, and what purpose do they serve? A considerable amount of work has already been expended. It is several years since Bruce Campbell announced that the program stars in our HF precise radial velocity program were proving to be constant while the IAU standards all varied! There has been an attempt to tie the results of precise radial velocity surveys to more extensive, lower precision, material and to extend the list to early-type stars. Any catalog of 'standard' velocity stars must be well distributed in velocity and cover both hemispheres. If different observatories use such standards to cross-check performance then, since velocity usually depends on epoch, the catalog will need to be kept up to date, preferably on the web.

The combination of improved velocities and highly accurate astrometric data from satellites such as Hipparcos have in many cases reduced the errors in orbital parallaxes below 1% leading to sufficiently accurate masses and absolute magnitudes to critically test evolutionary theories and answer questions about core convection. Exact orbital elements are particularly important for Cepheids, at least two thirds of which are in binary systems. It was surprising to learn that the physical elements of the α Cen system are still so poorly known and that the putative planetary candidate found with the fine guidance sensor of HST is not confirmed by PRV.

3. Nonradial Pulsations

Some of the most exciting results presented were on nonradial pulsations.

3.1. Solar-type Oscillations

The revelation of interior structure from fine splitting in the frequency spectrum of stellar oscillations has been the subject of many other symposia and we were lucky to have here several of the pioneers and major contributors in the field. While the associated micro-magnitude variations can only be monitored from space, ground-based PRV are the only way for the foreseeable future to accumulate surface velocity data from low degree modes. The results presented independently by the Colorado and Meudon groups for Procyon appear to be the first credible detections of oscillations in another solar-type star, albeit one evolved to a sub-giant where the natural oscillation periods are closer to 20 rather than 5 minutes. Maybe, by the time we meet again, these two groups will have collaborated with others to monitor Procyon globally and that its interior structure will be a solved problem.

3.2. roAp Stars

We saw some remarkable results for several of these slowly rotating A to F main-sequence stars which have strong magnetic fields inclined to their rotation axes. The heavier metals tend to concentrate near the magnetic poles. The stars oscillate in high radial overtones with a series of closely spaced periods of a few minutes. The velocity amplitude is strongly wavelength and line dependent with some lines showing spectacular velocity excursions while others show none. The validity of using $2K/\Delta m$ to characterize the variability was thrown into question.

3.3. δ Scuti Stars

These stars exhibit several nonradial modes simultaneously with typical periods of an hour or two and there are many groups active in this field. The rapid rotators allow us to identify the different modes and compare them with models. These stars particularly highlight the need for global networks such as MUSICOS to reduce the effects of sidelobes in the window function. We can only hope that 4-m class telescopes around the world will become increasingly available for this kind of program.

3.4. Late-type Giants

Being bright, with a large number of sharp, deep lines in their spectra, many of these stars were once considered convenient radial velocity standards. However, they have mostly turned out to vary by tens or hundreds of ms^{-1} over a wide range of time scales. Arcturus sometimes changes velocity by tens of ms^{-1} between nights, while at other times not at all. It also shows large, apparently periodic, variations over months and years. While the degree of velocity variability seems to depend on the level of chromospheric activity, it is not clear what basic mechanism or mechanisms cause the variability. These stars are bright and excellent objects to monitor with a small telescope. Their velocity changes are large enough to use telluric lines as fiducials and we heard a lot of interesting discussion about progress in this technique.

3.5. Doppler Imaging

There continues to be considerable progress in the methods of mapping stellar surfaces. By using a large number of lines simultaneously the technique has been extended to fainter stars. We heard about the high level of surface resolution now possible for the magnetically active late-type stars and about the persistent spots at their poles and the life-times and migration of spots at lower latitudes. This field demands considerable care and quality, high resolution spectrographs to fully resolve the intrinsic stellar line profiles. There was also an interesting discussion on the degree to which a Doppler image corresponds to the true light distribution on the stellar surface.

4. Planet Searches

4.1. Surveys and Distractions

The discovery of the short-period, candidate, Jupiter-mass planet around 51 Peg gave a huge impetus to activity in this field. We heard of a variety of PRV planet search programs underway with a wide range of techniques from Fourier transform spectrometers, conventional échelle spectrographs with I_2 vapor and Fabry-Perot etalons as wavelength fiducials, to high-stability, bench-mounted, fibre-fed spectrographs with double scrambling. There are plans afoot to observe over 1000 solar-type stars to $m_V = 8$ in both hemispheres with a goal of 3 ms^{-1} long-term precision for the brightest stars. In the short run, this will improve enormously the statistics and knowledge of short-period systems, but we shall still have to wait at least a decade to see if there is a significant number (or any!) solar system analogs.

The difficulty of establishing a precision of a few ms^{-1} in the presence of stellar variability has been acknowledged for many years. Table 1, reproduced from a talk I gave in 1993, lists the velocity noise sources which can be introduced by the star. One person's noise is someone else's science and the physics of each of these phenomena was carefully discussed over the past five days. To achieve a few $\mathrm{m\ s}^{-1}$ precision in searching for planets, one can only calibrate those variations considered predictable and take repeated observations to reduce the impact of the others.

Table 1. Intrinsic velocity variability of Sun-like stars

cause	time-scale	amplitude	predictable
NRP	minutes	1 ms^{-1}	no
rotation	month(s)	$\sim$10 ms^{-1}	yes
magnetic cycle	5 – 15 y	$<$3 ms^{-1}	yes
chromospheric	all?	unknown	not so far

In selecting stars for the large PRV survey programs, the close correlation between rotational velocity and RV noise, limits the sample to slow rotators. The RV noise associated with rotation has presumably something to do with the level of chromospheric activity. Figure 1 shows the acceleration which we measured with the HF PRV technique for the GV 5 star, κ^1 Cet, over 12 years and the simultaneous changes in the chromospheric activity reflected in changes to the equivalent width of Ca II λ8662. One can see that between 1987 and 1989 the star developed a large S-shaped velocity excursion of some 100 ms^{-1} which mimics an elliptical orbit but which is exactly tracked by the chromospheric activity, strongly pointing to the star as intrinsically variable. I put this in as a caution to encourage those involved in surveys to simultaneously measure some index of chromospheric activity otherwise we shall not be able to rule it out as a reason for velocity variability.

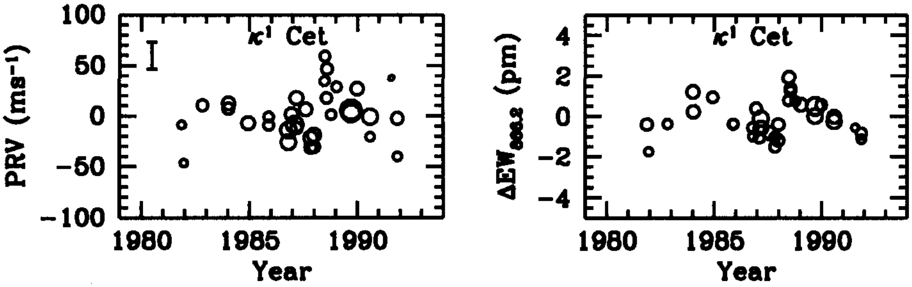

Figure 1. HF absorption cell differential velocities for κ^1 Cet (G5 V) and changes in equivalent width of Ca II λ8662. The latter is sensitive to chromospheric activity. The large change in velocity between 1987 and 89 is closely related to chromospheric activity and unlikely to have anything to do with a low-mass companion. The bar is a 2σ error and the area of each circle proportional to its inverse square internal error.

4.2. The Planets

A new candidate, Gliese 876 ($M \sin i = 1.5 M_J$, $a = 0.2$ AU) was added to the nine already acknowledged prior to the meeting and several more strong suspects were presented with further announcements expected throughout the summer. There was lively informal discussion about whether the current crop should be referred to as 'candidate planets' or acknowledged simply as 'planets'. The predominance of short-period systems seems real with a possible paucity of orbits $\sim$ 1 AU. The candidate primaries have significantly high metallicity. As to confirmation, the chance of detecting a transit by one of the short period systems is considered high and the stars are being followed in complementary photometric programs.

Given the level of effort expended in the PRV program, I was surprised that no reference was made to the importance of the infrared in the detection of some of the hotter planetary secondaries. For example, τ Boö B has an orbital speed $\sim$150 km/s and, with $T_e \sim 1600$ K, must be $\sim$2 mag more luminous ($\sim m_H = 12$) than Gliese 229B making it $\sim 2.5 \times 10^{-4}$ as bright as τ Boö A at 1.6 μm where CH_4 absorption bands make a gas-giant quite distinct from the sparse solar spectrum. A conservative estimate of sensitivity suggests that with $\sim$20 nm spectral coverage near 1.6 μm on a 4-m telescope and an hour's exposure per night, one could detect the spectrum of the secondary phase-sensitively over a single cycle of the 3.3 night orbit. Someone ought to try.

4.3. Brown Dwarfs

We learned that the frequency of planets probably increases towards low mass while falling rapidly above some 2 to 3 Jupiter masses. There is also evidence that the mass function of substellar objects appears to drop nearly to zero below $\sim$100 Jupiter masses and that the overlap of these two minima explains the marked deficit of brown dwarf companions. It was suggested the the bifurcation can be understood by the different way in which planets and stellar companions form. The former from a protoplanetary disc, the latter by fragmentation of the original proto-stellar cloud.

A possible brown dwarf companion ($30M_J$, $P = 530$ d) to Gliese 433 has been detected astrometrically by Hipparcos and in speckle images. The candidate brown dwarfs detected earlier by PRV appear now more likely to be sub-stellar rather than brown dwarfs. This raises the interesting question, are Gliese 433B and Gliese 229B rare massive planets or rare substellar companions? Maybe one of each! It would be very interesting to see whether Gliese 229B has any 'Galilean' satellites. The radius of the habitable zone around Glies 229B is only ten times its radius - analogous to the orbits of the Galilean satellites about Jupiter or the short-period planets about their parent stars. But the mass of Gliese 229B is only $40M_J$, so that the acceleration induced by even an Earth-mass planet in its habitable zone ($P < 1$ d) would be detectable, with existing techniques, in the infra-red.

5. The Instruments

None of this exciting science would have been possible without the exceptional quality of the associated spectroscopic and interferometic equipment and the ingenuity and dedication of those who built them. There was an intriguing suggestion of a split pupil arrangement to increase throughput. In some cases the auxiliary instruments appear to have quite outgrown their telescopes.

5.1. Spectrographs

Although we discussed two basic types of measurement:

(a) precise radial velocities,

(b) accurate line profiles,

it was not clear to me that in the search for perturbations by planets, that these two types of measurement could be completely separated if intrinsic velocity noise of the stars is to be defeated.

(a) In this, the principal challenge is the critical stability of the wavelength calibration over many years. When a star is observed at different times of year, barycentric motion can displace stellar spectral lines by up to 60 000 ms^{-1} relative to fixed wavelength fiducials. A precision of 3 ms^{-1} therefore demands complete knowledge of the point spread function, dispersion, and the fiducial wavelengths. Natural fiducials imposed by a captive gas are easy to maintain and systems such as the I_2 absorption cell are also easy to use, especially when the spectrograph and telescope are shared and there is no control over spectrograph stability. On the other hand, I_2 limits one to some 100 nm of spectrum.

At this meeting, it was demonstrated that dedicated, partially evacuated, temperature stabilised, bench-mounted spectrographs can achieve a similar precision with a fiber feed and double fiber scrambler together with conventional arcs to monitor spectrograph shifts plus fringes generated in either reflection or transmission with a Fabry-Perot etalon which can even be tuned to compensate for barycentric motion. For these spectrographs, one can improve the multiplex advantage with very broad wavelength coverage. But it is clearly still a fine art to get fibers functioning efficiently.

The results presented at this colloquium from both techniques are really impressive but I was unable to decide which would be the best bet for long-term planet searches, especially for the ≤ 10 ms^{-1} amplitude, decade-long period signals we must anticipate for analogs of the solar system.

There was a suggestion that a resolution of about 40 000 is optimum for planetary search programs. I am concerned that if one does not resolve the spectral lines in late-type stars with $R > 100\,000$, information on the noise sources in Table 1 affecting the line profiles will be lost and limit the credibility and understanding of any low-amplitude variables that might be discovered. One need no longer be detector size limited at high resolution with mosaics of large CCDs now coming into regular use.

(b) For line profiles there is no question that $R > 150\,000$ to 10^6 or more is mandatory and we also heard how Fourier transform spectrometers with their large étendue are the systems of choice for the purest profiles.

5.2. The Future

The prospect of really exciting advances in stellar astrophysics seems assured through the medium of precise radial velocities. I wonder what the highlights will be when we meet five years from now?

Discussion

Hearnshaw: I am delighted you mentioned the work of C.H. Buys-Ballot, who in 1845 demonstrated the validity of the Doppler effect for sound waves by playing musical instruments on passing trains. On the other hand, the optical Doppler effect took nearly half a century to be confirmed, and it was only in 1888 that Vogel measured the first reliable stellar radial velocities, 46 years after Doppler's work. In the case of both acoustical and optical Doppler effects, new technology (railway locomotives and photography) helped validate the effects sought. With future asdvances, for example in asteroseismology and extrasolar planets, new technology may well once again bring about the progress we seek.

References

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