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Discovery Potentials in High Time Resolution Astronomy: Things that Go Bump in the Night

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There is probably no subfield of optical astronomy (astrophysics, cosmology, solar physics, planetary science…) that could not benefit from photometry, spectroscopy, resolved imaging, or polarimetry with sharper time resolution or better cadenced observations. The same can, of course, be said for better angular and spectral resolution and for observations across all the other wavelength bands. The concentration here is, however, on optical and near infrared time resolution, in light of the focus of the meeting on extremely large (OIR) telescopes. Following a sort of historical introduction, the subsequent sections step outwards from the inner solar system to the universe, attempting to catch all the relevant (and probably some irrelevant) phenomena that the author could think of. A large fraction of the presentation consisted of light curves, taken from a number of different publications, including Sterken & Jaschek (1996), selected at least in part to indicate that photons often don't come labeled with source names, and sources often don't come with types indicated, and so could easily be mistaken for something else or not be identified at all.

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[1] Speaker

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1. Introduction, Definition, and Apologia

For the first 250 years of astronomy, the only time resolutions were those of the human eye (about 1/15th of a second) and the observer's notebooks (hours to years). Reports of rapid and/or extreme variability among the objects of study in this period are rather few – at least partly because the naked eye stars are nearly all OBs, giants, and supergiants, not M dwarfs, but the Chinese reported more than the Europeans, indicating some additional selection effect. Photography permitted more detailed comparisons across time scales from hours to decades, and showed that changes in things we now call galaxies and nebulae were a good deal rarer than the pencil astronomers had found. The sun was, of course, the first flare star (Carrington, 1859), and even as we were meeting the Solar Dynamical Observatory was sending back data showing that the combination of continuous coverage and 10-second time resolution can be very informative. UV Ceti is the prototype of the others, its normal magnitude around +13 indicating that such things are moderately rare, and its name indicating that this sort of variability is not all that easy to discover, though it flares up to m = + 7.

Extension to shorter time scales required assorted photoelectric and photon-counting devices. The recognition of the 0.033 second period of the Crab Nebula pulsar using phase-coherent imaging with a 36" telescope remains a remarkable achievement in this domain (Cocke, Disney & Tayler 1969). One cannot help but wonder whether there are other things out there that might never be recognized because there is no guidance from radio data.

Several speakers provided definitions of HTRA ranging downward from seconds to nanoseconds, depending on the phenomena that interested them. Since you are unlikely to see something unless you look for it and unlikely to look unless you suspect it is there, I would like to provide a broader definition: smaller Δ t or more regular/appropriate cadencing than has been previously available. This sometimes implies very frequent visits – even well known dwarf novae and flare stars have most of their rises poorly resolved, and Mira, the first (semi) regular variable has holes in its decades of light curves. Good coverage with time resolved (or phase resolved) spectroscopy and polarimetry are still rarer.

An important property of extremely large telescopes is, therefore, that they can (if the users so choose) provide more, and more closely spaced, observations of more sources. One might, therefore, have caught the formation of the new ring of Jupiter reported by New Horizons this year, which apparently came about when satellite S/2000 J11 was torn apart by Himalia. Or you could follow multiwavelength changes in the Great Red Spot or monitor flickering during the formation of massive stars that is likely to arise from Rayleigh-Taylor instabilities between the incoming disk gas and outgoing jets. (Peters et al. 2010; the solar system items appeared recently in Science News or Sky & Telescope).

One last introductory matter needs attention – how, in a group with so many experts, did I come to be making this presentation? It is clearly a matter of tradition, following upon Trimble (1994, the concluding remarks at a Tucson meeting on high resolution spectroscopy, 1998, on the nature and significance of surveys, and 1999 on astronomical incentives to improve angular resolution). Another way of saying this arose when an anonymous colleague some years ago congratulated me on my election as President of the IAU Commission on Galaxies "for your well-known work on galaxies." The even more anonymous response was, "Well, these jobs are generally done by the people who are willing to do them."

2.0 BRIEF HISTORICAL EXAMPLES

Here are a handful of cases where, indeed, the photons did not come labeled. Back when variability of the sky (apart from comets, meteors, and such, then all thought to be atmospheric) was a somewhat revolutionary idea, Fabricius reported a nova in Cetus in 1596. Holwarda then reported in 1638 a star in the Whale that was not in Ptolemy's catalog. Helvelius in 1662 figured out that the two were the same variable star, and Boulliau reported periodicity a little later, suggesting a spotted surface and rotation (like the sun, only more so) as the cause. Now variously called Omicron or Mira Ceti, it is the prototype of the semi-regular, long period, pulsational variables, with an amplitude of at least 8 magnitudes and a period of 80-100 days, despite which our knowledge of the range of shapes of its light curve from period to period remains incomplete.

BATSE trigger number 1141 (GRB 911202) was double-peaked, with the second peak higher and a trailing tail of about 20 seconds. A similar-looking profile starting within a couple of seconds of the trigger time might predispose you to say "a ha! Counterpart," until you hear that the second "light" curve is actually the output of one of Joe Weber's room-temperature bar detectors for gravitational radiation (Weber & Radak, 1996).

One of the goals of HTRA is the search for new sorts of sources, particularly transients (Di Stefano et al. 2009). Whether all the unwanted variables you find are background or foreground depends on what you are looking for. I have called this phenomenon:

Two dwarf novae, seven flare stars, and a bird
That flew across our dome slit on the third.

The problem is exacerbated by the light curves of the unwanted variables taking a wide variety of forms. Dwarf nova phenomena discussed by Payne Gaposchkin (1957), include the nearly regular 4-magnitude fluctuations of SS Cygni, long standstills by RX And, a prolonged maximum for T Aur, followed by 11 magnitudes of fading, and 6 magnitude outbursts of WZ Sge, separated by such long periods of inaction that it was long classed with the recurrent novae (nuclear outbursts) rather than the dwarf novae (accretion-fueled outbursts).

The flare stars are even worse, for their light curves sometimes mimic other phenomena (if not more interesting at least currently more sought after). For instance, you would swear that Fig 2.30 of Sterken & Jaschek (1996), is a binary microlens and Fig. 2.32 the counterpart of a gamma ray burst. In fact they are UV Ceti and EV Lac.

As for the bird, it is perhaps mythological (and would, of course, yield a 100% occultation of any point source, with no Fresnel fringes), but monitoring by the Santa Barbara Astronomy Group of known GRB error boxes in the late 1980s recorded one coincident trigger between two stations 10.4km apart which eventually provide to be a bolide (Schwartz et al. 1992) occurring at the height of the 1988 Perseid meteor shower and seen by many people. A bolide, incidentally, is a fireball seen by a geophysicist. For reasons I don’t understand, this remark got the loudest laugh of my talk.

Imaging with the wrong time intervals can also get you into trouble. From 1939 to 1957, Walter Baade took roughly annual images of the Crab Nebula (first with the 100”, later with the 200”) though filters designed to emphasize the line emission and continuum emission separately. The series was continued, with less frequent exposures, by Guido Munch, and the pile of continuum plates handed over to J.D. Scargle to analyze as part of his Ph.D. dissertation (Scargle 1969). The early Baade images suggested possible periodic, in and out, motion of a thin wisp near the center of the nebula, and Scargle suggested that the same phenomenon had continued after Baade died and stopped taking plates so frequently. The drawing, as presented, at one conference, reminded a distinguished colleague of the canals of Mars, and more recent better-timed HST images have been interpreted as a succession of filaments forming and moving outward. As for the line emission plates, I got those and used them to demonstrate (monotonic, non-controversial) expansion of the nebula and proper motion of the pulsar.

3.0 TRULY DIFFUSE ENTITIES

One might suppose that diffuse gas and dust would be non-starters in this race. The exceptions that come to mind (and none is likely to happen very rapidly) include shock waves moving through gas or dust or both (changes, for instance, in pulsar wind nebulae), photoevaporation of dust grains (when a GRB zaps them), and changes in filamentary gas along the sight line to something bright. The first requires imaging and the latter two spectroscopy, before, during, and after, as it were. A non-spectacular case is the rapid variability of recurrent nova U Sco near peak light, which is probably variable obscuration in clumpy ejecta (O'Brien 2010), through the 35-second X-ray period could also have been a new sort of instability in the nuclear burning on the surface of the white dwarf.

4.0 SOLAR SYSTEMS AND THEIR CONTENTS

The phenomenon closest to home is scintillation – not seeing, but the blurring of time resolution due to photons taking slightly different lengths of time to get through the atmosphere to the detector. Beckers (2010), has noted that a large(ish) telescope doing HTRA should, therefore, have a small scintillation monitor focused on something bright nearby.

Comets might well be examined by phase-resolved spectroscopy in the solar system, telling us about non-uniform surfaces as they rotate. They can impact on moons, planets, and stars, with probable examples of all three in our solar system. It is not guaranteed that exo-comets exist, and detecting any of their rapid activities will be a challenge. SL-9 hitting Jupiter is the best known local example; many comets have been swallowed by the sun.

Similarly asteroids (main belt, KBO, and near-earth orbiters) undoubtedly rotate (often with periods of hours) and can collide with others of their ilk as well as with planets and moons. Interesting HTRA cases including wanting to know the rotation periods of all NEOs so as to pick a slowly rotating one for astronauts to explore (as an alternative to the moon or Mars) and looking at Haumea in the KBO which rotates so rapidly that it is probably a Jacobi ellipsoid rather than Maclaurin spheroid (Lacerda 2010). In addition it has a dark red spot, and phase-resolved spectroscopy is likely to be able to say something about the different compositions of the different colored regions and, therefore, whether causes might include initial inhomogeneity, an area knocked off by the collision likely to have spun it up, or something else. An asteroid-asteroid collision (with one surviving and the other strung out as dust) was reported recently for a main belt object as the most likely interpretation of the morphology. Again detection in other systems counts as challenging!

KBOs can just about occult stars since 100 km at 10 AU is 0.02". Reported occultations of X-ray sources by asteroids a few years ago was probably a false alarm, however. The light curves will be all fringes, with no totality phase of the sort one associates with lunar occultations!

A topic of some relevance to habitability of other planetary systems is the issue of "late heavy bombardment." You might suppose that repeated K-T boundary events would be bad, but it has been argued that most of our supply of volatiles came from comets and asteroids, formed well outside 1AU, during the early phase of solar system evolution. Detecting light flashes from bombardment of exo-earths again counts as challenging.

Moons in our own solar system can display interesting variability, telling us about synchronized or non-synchronized rotation, collisions, surface features, and weather. Io pops out a new volcano from time to time, and sufficiently close monitoring might associate these (or fail to associate them) with times of greatest tidal stress. Impacts of comets and asteroids on moons will make flashes and probably new craters. There is a long and spotty history of reports of such things (and denials of them) on our own luna. Our favorite 600-meter telescope in space could decide how typical solar system phenomena are. Presumably there are exo-planets with large numbers of moons capable of mutual events like the moons of Jupiter and Saturn (eclipses, transits, occultations and all).

Moving on to planets, we find changes in known features (significant changes in Jupiter's great red spot, whose study required multiwavelength data on a variety of time scales, announced by G. Orton of JPL in March) and features that come and go (several on Neptune over the years, and "son of red spot" on Jupiter). Saturnian aurorae, associated with its rapidly rotating magnetosphere, (Bruce 2010) presumably also have exo-planet analogs. Phase-resolved spectra through the ingress and egress phases of exo-planet transits and occultations seem to be our best hope of identifying earth-like atmospheres (again, not immediately), and those phases are quite short-lived. More spectacular events are possible. There is a very small chance that the slightly erratic orbit of Mercury could become more so (driven by Jupiter) and, in turn, eventually destabilize the entire inner solar system. The resulting close encounter of earth and Mars (another Sky & Telescope item) would turn both into glowing blobs of lava in just a couple of hours. Watch in the infrared!

Brown dwarfs and orphan planets, at least when young, are bright enough that one might probe their weather and surface features with rapidly-cadenced spectra.

Might HTRA be relevant to optical SETI? Not, I suspect, in any very happy way. A nuclearly-armed civilization might blow up most of its planet in a detectable way. And it was suggested long ago that a class II civilization could call attention to itself by dumping enough europium (for instance) into the atmosphere of its star to produce a sudden spectroscopic change.

5.0 STARS

This is probably the largest class to be explored, since stars at both the beginnings of their lives (FUOrs and all) and the ends (supernovae), sometimes in the middle (flare stars) and more often when in pairs (all the flavors of cataclysmic binaries) are capable of rapid changes in brightness, temperature, atmospheric composition, and so forth.

In star formation regions, we indeed observe phenomena connected with rapid change in accretion (or excretion!) disk structure in the FUOr's (prototype FU Ori), EXor's (prototype EX Lupi just to make it more difficult), and of course, the less spectacular T Tauri and Herbig Ae/Be stars. A newly-predicted phenomenon is Rayleigh-Taylor instability during the formation of massive stars by accretion, so that gas can come in, but also get out when the accretion luminosity exceeds the Eddington limit (Peters et al. 2010).

On the main sequence, there can be pulsation (both radial and non-radial, nearly adiabatic and non-adiabatic), rotation of non-uniform surfaces, and orbital motion with eclipses, shape distortions, and mass transfer. I have attempted many times to make a complete list of all the sorts of known variability (and a few that one might expect but does not see, like radial pulsation of neutron stars). The commonest failure mode is getting bored and going off to do something else, realizing that I have left out either the W Vir stars (one sort of Population II Cepheid) or the GW Vir stars (pulsating white dwarfs with very high temperatures and mostly He, C, and O in their atmospheres), not to mention either RS CVn or α^2CVn (the former are close binaries with occasional eruptions, the later stars with strong magnetic fields holding in spots of anomalously strong Eu lines and such, so that their spectra vary through the rotation period), or, if you wish, either R CrB (sudden, unexpected fadings plus Cepheid-type pulsation) or T CrB (both a recurrent nova and a symbiotic star).

A bit more useful, perhaps, to try to put them into evolutionary sequences (even now I would disown rather little of (Trimble 1983), which does this for close binaries). Several standard textbooks of stellar structure and evolution (even Hansen, Kawaler, & Trimble 2004) take a cut at single stars. But all such efforts are doomed to failure in the face of stars like YY Gem, which is an eclipsing binary (dM1e + dM2e), that also exhibits flares and starspot waves (Sterken & Jaschek p. 120).

At least two possibilities remain, given our goals. One is a culling of the most rapid known variabilities and attempts to understand them. The other asks which puzzles connected with variable stars might yield to a larger, better cadenced data bases. Some of these latter have long traditions, for instance the curious fact that masses of Cepheids determined from pulsation properties tend to come out smaller than those from evolutionary tracks passing through their positions in the HR diagram. Some combination, one supposes, of incorrect treatment of mass loss in the evolutionary tracks and incorrect assignment of modes (1st and 2nd overtones etc.) in the pulsation analyses. But if I knew of a specific observational program that could yield a definitive answer, I would be out pursuing it.

The shortest-duration phenomena are necessarily associated with compact objects – white dwarfs, neutron stars, and black holes, which you might also call cataclysmic variables, pulsars, X-ray binaries, gamma ray bursts, and radio transients. One would like mode spectra of WDs and NSs with enough precision to constrain the equations of state, a definite decision on whether SS 433 is a neutron star or a black hole, some sort of independent confirmation that the energy source in anomalous X-ray pulsars really is an enormously strong magnetic field, and further information on the progenitors of Type Ia supernovae. These are important for nucleosynthesis and as cosmological standard candles, and whether they arise from mass transfer onto white dwarfs of nearly the Chandrasekhar mass from normal stars or from mergers of two WDs of total mass greater than $1.4M_\odot$ and orbit period less than eight hours remains to be determined. Gilfanov & Bogdan (2010) conclude that nearly all must be double WD mergers in early type galaxies (because they don't see the X-rays that would be expected from the 10^7 year lead-up to explosion in the other case). But no suitable WD pairs are known in the Milky Way. Finding them would require phase-resolved, high wavelength resolution spectroscopy of a large number of faint stars with short orbit periods.

High time resolution astronomy is clearly of use for all of these, though in some cases X-ray or radio data may trump optical/NIR. Some of these battles are also very old, for instance the nature of the underlying instability in dwarf novae, and whether it occurs in the accretion disk (the majority view for long enough that other possibilities have almost been forgotten) or in the donor, non-compact star. One version of the conventional wisdom is to be found in Smak (2010) and I was reminded of the alternative by a hand-written letter last month from G.T. Bath (relevant paper, Papaloizou & Bath 1975). But higher time resolution won't help there!

There is, however, still a good deal of "discovery space" out there. This is a list of my favorites, given as NASA bullets because I don't know how to prioritize or classify them better.

- Eta Carinae and her ilk – luminous blue variables that may be on their way to doing something else. SN 2006jc flared up two years before exploding, and it would be wonderful to assemble a large enough set of "pre-need" images of stars that later turn up as SN II's to be able to say whether increasing variability over a few years constitutes a "supernova early warning system". Rising neutrino emission would, but we don't know how to do that yet.
- MACHO star-star light curves and all the other variables found in such searches that are either signal or noise, depending on your goals. I find it striking that the OGLE project, which has found a great many RR Lyrae's, eclipsing binaries, and so forth, also has a large class called "MISC", meaning not (yet) of identifiable types (Udalski, et al 2005, and many other papers both earlier and later in the series).
- Star rotation and eclipses, surface brightness vs. r and θ (Doppler tomography, and of course spectra ditto).
- Black hole eats star. There are one or two candidates at the SMBH, galaxy level, which happen slowly, but the possible disruption of a white dwarf by an IMBH in a globular cluster (Irwin et al. 2010) might have been fun to watch in real time.
- Flickering of CVs and XRBs (well covered in other talks).
- New types of supernovae. According at least to press releases, 2007if had a white dwarf more massive than the Chandrasekhar limit, and another recent event seems to have involved the death of an AM CVn star, not to be confused with RS CVn or α^2CVn, but rather a very close pair of helium white dwarf, with total mass considerably less than the stability limit.
- Flare star populations in clusters, tracked for long enough to explore dependance on mass (with age and composition factored out) of amplitude, flare frequencies, and cycle lengths
- Explosive events with maximum M_V between ordinary novae and the faint supernovae. V838 Mon is perhaps the best-known example. Others are discussed by Kasliwal & Kulkarni (2009). Possible mechanisms include planetophagia, stellar collisions, accretion-induced collapse (a classic idea for resolving statistical discrepancies in the numbers of millisecond pulsars vs. their XRB ancestors in globular clusters and elsewhere), very large amounts of fall-back, and undoubtedly many things that have not been thought of.
- Orphan GRB afterglows.
- Anything with jets end-on to us – YSOs, SNe, CVs, PNe, AGNs and all.
- Unexpected dimmings, and I suspect that the discovery space may be larger for these than for unexpected brightenings.

- Real-time stellar evolution, of which FG Sge is the best known case.
- FK Comae stars. These are rapidly rotating giants, perhaps arising from stellar mergers.
- Stars that can walk and chew gum at the same time, like the eclipsing RR Lyrae's in the OGLE data base and HD 5980, which is an eclipsing Wolf-Rayet in the SMC.
- Types whose discovery has been recent enough that they must surely still hide secrets, like the roAp (rapidly oscillating, peculiar A) stars, Gamma Doradus stars, and slowly pulsing B stars, the umpteen-mode sdBs, and , at the other end of time, the Maia variables which have probably been voted out of existence.
- IMBHs are good for things besides eating wayward stars. The are, perhaps, the remnants of Population III, whose numbers and masses are, therefore, of importance in the high-profile, origins-type questions. Cores of globular clusters are perhaps as good a place to look for them as any. And because their last stable orbits will have periods of seconds, HTRA is conceivably useful in establishing their existence and properties.

But we are once again approaching perilously close to the cliff of trying to figure out just how many sorts of variable stars there are and how they fit into evolutionary scenarios and very different timescales of variability, from milliseconds for some of the X-ray binaries to a century or more for the changes in spectra of a few magnetic white dwarfs with complicated field patterns but no detectable changes so far. And we have already fallen off another cliff edge--the one marked by the combination of rarity and unexpectedness, so that only very large scale surveys have much hope of discovering them or showing that they are different from known classes.

At this point, properly-timed follow-up data became essential, as has long been recognized for supernovae, novae, and gamma ray bursts. But whether you truly need the E-ELT or the Las Cumbres Global Telescope Network of one and two-meter mirrors will suffice, will depend not only on the time resolution needed to answer your questions but also on how much spectral and angular resolution are simultaneously required.

Astronomers want it all, but only Galileo ever had it all to himself, and even he not for long, what with counterclaiments to the discovery of sunspots and all.

6.0 HTRA AND THE "BIG" QUESTION

A rapidly-increasing number of decadal and other review panels in the United States, Europe, Great Britain, and elsewhere, while nominally prioritizing future facilities are, in effect, also prioritizing the kinds of science to be done with them. Better understanding of the physics of strong gravitational fields is typically one of the high-priority topics. For this, the rapid variability of sources connected with black holes, neutron stars, and (maybe) white dwarfs is obviously important, and since things can happen in intervals as short as a millisecond, HTRA is clearly important, though dragging of inertial frames (e.g.) seems to be an X-ray phenomenon. The jets and disks of active galaxies display many of the same violent variabilities as do those of CVs and XRBs, for instance a major change in optical polarization at the time of a gamma ray flare of 3C 279 (Abdo et al. 2010), but the time scales are days to weeks, rather than seconds, because of the much larger Schwarzschild radii.

Most of the other "big" questions, however, deal with origins of various kinds: the very early universe (including inflation and the nature of dark matter and dark energy), first lights and their remnants, structure formation (meaning the lumps that become galaxies and how they merge to do so), formation of stars (especially stars with planets) and the detection, characterization, and potential habitable of planets orbiting other stars.

Possible instabilities in protoplanetary disks and the SETI-opportunities were mentioned above. What about the rest? Short optical flashes are likely to result from the decay or annihilation of some kinds of dark matter particles and also from the evaporation of primordial black holes (a possible inflation or big bang relic). But only extended surveys of large chunks of sky would seem to have any chance of catching these. Intermediate Mass Black Holes are possible remnants from very massive population III stars, and if some of these have ended up at the centers of globular clusters, then staring at some of these (probably the most massive) might pay off, without requiring a wide field of view. As for the rest, I am not so sure, but see Shearer et al. (2010) for a more optimistic view.

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