PARALLEL SCIENCE WITH ASTERO-SEISMOLOGY MISSIONS

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Abstract
Eddington, COROT, MONS, KEPLER, and the other asteroseismology and planet finding missions, obtain extremely high photometric quality time-series data as their primary purpose. Similar quality data are potentially, and in some designs actually, being obtained for very many other sources in the telescope field of view, in addition to the primary mission targets. These parallel data, of exceptional quality and broad scientific interest, can be made available for scientific analysis with small system impact. This paper lists some of the most obvious of the serendipitous research and discovery opportunities which these parallel data will allow. The scientific potential is both large and unique, encouraging efforts to provide these data to the community.

Key words: Stars: variability, binaries – X-ray sources – Accretion physics – Supernovae – extragalactic astrophysics

1. Introduction
High precision time-series photometry is the method of choice for study of many astrophysical objects. These obviously include astero- and helio-seismology, and searches for low-mass planets eclipsing their parent stars, the subjects which have justified a series of dedicated spacecraft projects. The generally large fields of view of these missions, especially in their planet-finding mode of operation, at least in principle allow time-series photometry free of the Earth’s atmospheric disturbances for many other sources in that field of view which are not primary targets.

Delivery of this parallel science data stream for analysis is necessarily subject to the technical constraints set by the primary mission science, especially such factors as telemetry, sampling frequency, number of objects, on-board processing capability, and so on. Nonetheless, parallel science has a proven record of discovery (pace HST), and is manifestly a cost-effective use of resources, so that its optimisation is a legitimate factor in mission design.

We note here some of the scientifically most obvious, and technically least demanding, parallel scientific studies which can produce important and unique science from missions whose primary purpose is asteroseismology and/or planet finding. Examples of the science applications, and indications of the number of sources available for study, are provided. We do not discuss here pulsating stars, wherever they exist in the HR diagram, as such stars are core science for asteroseismology, not additional science.

We consider in turn the following:
1. Solar System Objects
2. Young Stars
3. Low Mass Stars
4. Eclipsing Binaries
5. Accretion physics
6. AGN and QSOs
7. Supernovae
8. Low surface brightness galaxies
9. Gravitational lensing

2. Solar System Objects
The minor bodies of the Solar System record physical conditions in the proto-Solar nebula, and their properties therefore shed light on the formation of planetary systems. This is naturally a complementary aspect of planet-discovery, a primary science goal. Discovery and orbital determination of near-Earth objects is also a subject of high public interest.

Solar system objects crossing the focal plane must of course be identified, and removed from primary target photometry. The data are also of intrinsic interest. By detailed surveys of specific directions, Eddington will discover substantial numbers of solar system objects. This survey is a natural complement to larger-area shorter integration studies. Eddington will naturally be very sensitive to slow-moving sources, which are those hardest to detect in normal surveys. The Eddington sensitivity limit reaches to the brighter magnitude regions expected to contain Kuiper-belt objects, which will have small apparent motion.

The angular motion of a typical Kuiper-belt object at ~90° elongation is small: the known Kuiper-belt objects have $da/dt = 0.02 – 1.0$ arcsec hr$^{-1}$ and $dδ/dt = 0.002 – 1.2$ arcsec hr$^{-1}$. That is, with the expected spatial resolution of present mission designs, Kuiper-belt objects are effectively stationary for times of hours, allowing long effective integration times. The surface density of the Kuiper Belt at $V = 20$ mag is $8 \times 10^{-3}$ objects per square degree, in the ecliptic plane, so that the very large area of sky observed is well matched to the surface density.
3. Young Stars

Optical photometric variability is one of the original defining characteristics of pre-main-sequence stars (Joy 1945). Although pre-main sequence objects are usually identified by other, less biased photometric and spectroscopic survey techniques now, modern variability observations remain a valuable probe of the stellar and circumstellar activity (e.g. Bouvier et al. 1995). Such monitoring studies have shown that photometric variability is a diverse phenomenon in that the observed flux can change by milli-magnitudes to magnitudes on time scales of minutes to years, often with periodic as well as aperiodic components. Young stellar objects are also variable at x-ray, ultraviolet, infrared, and radio wavelengths. For periodic stars, the variability is thought to originate mainly from cool magnetic or hot accretion spots on the stellar surface that are hundreds to thousands of degrees different in temperature from the photosphere and rotate with the star. Aperiodic variability may arise from mechanisms such as coronal flares, irregular accretion of new material onto the star, and temporal variations in circumstellar extinction.

An example of the incidence of photometric variability is provided by a recent study by Carpenter et al. (2001) of a part of the Orion Nebula Cluster. They established the near-infrared variability properties of pre-main-sequence stars in Orion on time scales up to 2 years. A total of 1235 near-infrared variable stars were identified, over 90% of which are likely associated with the Orion A molecular cloud. About 30% of their targets were detected as variable, in spite of their relatively high detection threshold.

The variable stars exhibit a diversity of photometric behavior with time, including cyclic fluctuations with periods up to 15 days, aperiodic day-to-day fluctuations, eclipses, slow drifts in brightness over one month or longer, colorless variability (within the noise limits of the data), stars that become redder as they fade, and stars that become bluer as they fade. The mean peak-to-peak amplitudes of the detected photometric fluctuations were about 0.2mag in each band and 77% of the variable stars have color variations less than 0.05mag.

The high surface density of such variables towards star forming regions is illustrated in Table 1. It is worth recalling that the Sun is presently moving through an expanding star-forming complex, well-mapped by HIPPARCOS data (e.g. deZeeuw et al. 1999). The local number of young stars is higher than might be expected from simple star count models. Thus, while Orion A is certainly an unusually high density region, all low Galactic latitude directions have a large number of young, and therefore variable, stars at apparently bright magnitudes.

The amplitude range of the Carpenter et al. variations suggests that higher photometric precision observations will show every young star to be intrinsically variable. The more extreme stars have amplitudes as large as about 2mag and change in color by as much as about 1mag. The typical time scale of the photometric fluctuations is less than a few days, indicating that near-infrared fluctuations results primarily from short term processes.

Rotational modulation of cool and hot star spots, variable obscuration from an inner circumstellar disk, and changes in the mass accretion rate and other physical properties in a circumstellar disk are possible physical origins of the near-infrared variability. Cool spots alone can explain the observed variability characteristics in about one-half of the stars, while the properties of the photometric fluctuations are more consistent with hot spots or extinction changes in about one-quarter of stars. Variations in the disk mass accretion rate or inner disk radius, while evident, are a minority variability source. Comparison of the observations and the details of variability predicted by hot spot, extinction, and accretion disk models suggest either that another variability mechanism may additionally be operative, or that the observed variability represents the net results of several of these phenomena.

### Table 1. Variable YSO Population Associated with Orion A

| Surface Density (arcmin$^{-2}$) | N   | N$_{ear}$ | f$_{ear}$     |
|-------------------------------|-----|----------|---------------|
| 0.25                          | 2704| 786      | 0.29 ± 0.010  |
| 0.50                          | 2148| 627      | 0.29 ± 0.011  |
| 0.75                          | 1881| 554      | 0.29 ± 0.012  |
| 1.00                          | 1488| 445      | 0.30 ± 0.014  |
| 1.25                          | 1262| 386      | 0.31 ± 0.016  |
| 2.50                          | 895 | 258      | 0.29 ± 0.018  |
| 3.75                          | 752 | 202      | 0.27 ± 0.019  |
| 5.00                          | 621 | 158      | 0.25 ± 0.020  |
| 7.50                          | 397 | 94       | 0.24 ± 0.025  |
| 10.00                         | 253 | 52       | 0.21 ± 0.029  |

3.1. Pre-planetary systems

An illustrative study of variability in the Pre-Main Sequence Star KH15D induced by eclipses by circumstellar dust features has been presented by Hamilton et al. (2001). This illustrates the potential of photometric monitoring to investigate pre-planetary structures in stellar disks, an elegant complement to the main planet-finding programme. KH15D is a pre-main sequence eclipsing TTauri member of the young cluster NGC 2264. The orbital period is 48 days and both the length (16d) and depth (3 mag) of the eclipse have increased with time. Brightening near the time of central eclipse is confirmed in Hamilton et al.’s recent data but at a much smaller amplitude than was originally seen. During eclipse there is no detectable change in spectral type or reddening, indicating that the obscuration is caused by rather large dust grains and/or macroscopic objects. Evidently the star is eclipsed by an extended feature in its circumstellar disk orbiting with a semi-major
axis of 0.2 AU. Continued photometric monitoring should allow studies of the disk structure with a spatial resolution of $3 \times 10^6$ km or better.

### 3.2. X-RAY EMISSION AND VARIABILITY

X-ray emission has played a major role in identification of young, nearby stars. The ROSAT All-Sky Survey (RASS) is an important tool for discovering stellar associations and investigating their X-ray properties. The new generation of X-ray observatories are powerful tools for discovery and study of young stars. For example, for coronal X-ray sources XMM has about an order of magnitude higher sensitivity than the RASS and provides much longer exposure times allowing continuous monitoring for more than 40 h. Complementary and coordinated studies between X-ray and optical monitoring is a valuable tool to extend, and perhaps complete, the local young-star census.

### 4. THE LOWEST-MASS STARS

Very low mass stars, even those which are not very young, have recently been shown to be intrinsically variable. Spots, magnetic activity, large convection zones, and even meteorology are all possible explanations. An illustrative study is that of the ultracool dwarf BRI 0021-0214 by Martin et al. (2001).

They report CCD photometric monitoring of the non-emission ultracool dwarf BRI 0021-0214 (M9.5). Significant variability in the I-band light curve at a period of 0.84 day is found, but appears to be transient because it is present in the 1995 data but not in the 1996 data. They also find a possible period of 0.20 day, stable over the year, but no periodicity close to the rotation period expected from the spectroscopic rotational broadening (<0.14 day). BRI 0021-0214 is a very inactive object, with extremely low levels of Hα and X-ray emission. Thus, it is unlikely that magnetically induced cool spots can account for the photometric variability. Martin et al suggest the photometric variability of BRI 0021-0214 could be explained by the presence of a active meteorology that leads to inhomogeneous clouds on the surface. The lack of photometric modulation at the expected rotational period suggests that the pattern of surface features may be more complicated than previously anticipated.

The magnetic Reynolds number (Rm) in the atmosphere of L dwarfs, which describes how well the gas couples with the magnetic field, is too small (<< 1) to support the formation of magnetic spots. Thus, these authors support the idea that non-uniform condensate coverage (i.e. clouds) is responsible for the variations. In contrast silicate and iron clouds form in the photospheres of L dwarfs. Inhomogeneities in such cloud decks can plausibly produce the observed photometric variations. Further evidence in support of clouds is the tendency for variable L dwarfs to be bluer than the average L dwarf of a given spectral type. This color effect is expected if clear holes appear in an otherwise uniform cloud layer.

A high level of magnetic activity in very late type stars, with associated flaring, has also been deduced from VLA observations by Berger (2001).

### 5. ECLIPSING BINARY STARS

Eclipsing detached binary stars provide key tests of stellar mass-luminosity-radius relations, tests which available stellar models struggle to meet (eg Lebreton, Fernandes & Lejeune, 2001; Bedin et al 2001). The corresponding stellar model tests complement the asteroseismology science case, and in that sense are core science for the missions, rather than additional science. We do not discuss this further here.

It is worth noting that such studies can extend stellar structure studies beyond single stars. Discoveries of eclipsing detached binaries, especially in open clusters, where independent ages can be provided, will revolutionise those fundamental tests of stellar evolution which include dynamical histories. As just one illustration, the star S1082 in M67 has been recently shown to be a triple, with inner and outer components being blue stragglers (van den Berg et al 2001). Study of such systems provides key tests of stellar evolution, binary coalescence, and the dynamical evolution of multiple systems.

For contact binaries, the distribution of the observed light-variation amplitudes, in addition to determining the number of undiscovered contact binary systems falling below some photometric detection thresholds and thus lost to statistics, serve as a tool in determination of the mass-ratio distribution, which is very important for understanding of the evolution and mass transfer.

Rucinski (2001) provides simulations of the expected amplitude distribution, which show that it tends to converge to a mass-ratio dependent constant value for sufficiently accurate photometric data. The strong dependence of variation amplitude on mass ratio can be used to determine the latter distribution. Estimates based on Baade’s Window data from the OGLE project, for amplitudes $a > 0.3$ mag allow determination of the mass-ratio distribution $Q(q)$ over $0.12 < q < 1$, and suggest a steep increase of $Q(q)$ as $q$ tends to zero. The mass-ratio distribution can be approximated by a power law, either $Q(q) \approx (1 - q)^n$ with $a_1 = 6 \pm 2$ or $Q(q) \approx q^{b_1}$, with $b_1 = -2 \pm 0.5$, with a slight preference for the former form. Both forms must be modified by the theoretically expected cut-off caused by a tidal instability at about $q_{\text{min}} = 0.07-0.1$. An expected maximum in $Q(q)$, is expected to be mapped into a local maximum in $A(a)$ around 0.2-0.25 mag. Clearly extension of such data below the current large photometric detection threshold will substantially enhance such statistical analyses.
6. Accretion disk stellar systems

This general class includes cataclysmic variables, dwarf novae, high-mass and low-mass X-ray binaries, and a host of other historical terminologies. The evolutionary state of the mass donor and of the recipient of the accreted mass define the categories, and the timescales and amplitudes of relevance. The basic physics is common to all classes.

X-ray binaries (XRBs) are close binaries that contain a relatively un-evolved donor star and a neutron star or black hole that is thought to be accreting material through Roche-lobe overflow. Material passing through the inner Lagrangian point moves along a ballistic trajectory until impacting onto the outer regions of an accretion disk. This material spirals through the disk, losing angular momentum, until it accretes onto the central compact object, where X-rays are emitted from inner disk regions.

In cataclysmic variables, additional variability is categorized as a superhump, a periodic modulation caused by a precessing eccentric accretion disk.

X-ray novae (XNe) are mass transferring binaries in which long periods of quiescence (when the X-ray luminosity is $\leq 10^{33}$ ergs s$^{-1}$) are occasionally interrupted by luminous X-ray and optical outbursts. XNe provide compelling evidence for the existence of stellar mass black holes, since they can be shown to contain compact objects whose mass exceed the maximum stable limit of a neutron star, which is $\approx 3M_\odot$. Observations of the companion star in quiescence can lead to a full understanding of the orbital parameters of the system, including the masses of the binary components and the orbital inclination (e.g., Bailyn et al. 1998).

A detailed understanding of the accretion flow in these objects is of considerable importance, since the behavior of the flow close to the event horizon may give rise to tests of general relativity in the strong field limits. During their outburst cycles, XNe generally display the complete range of spectral states, from quiescent (“off”) to “low/hard” to “high/soft” to “very high”. They therefore present unique opportunities to study all of these kinds of accretion flows in a situation in which the geometry of the binary system is well understood.

X-ray pulsars in high mass X-ray binaries (HMXBs) consist of an accreting neutron star orbiting a (super)giant or a main-sequence Be-type companion star. Most known neutron stars in Supergiant XBs emit high X-ray fluxes, driven by accretion of a roughly spherical dense wind from the massive companion (which may be enhanced by Roche lobe overflow).

In contrast, the neutron stars in Be-star X-ray binaries often exhibit transient X-ray outbursts which may occur periodically at periastron (type I) or when the companion star undergoes a mass loss episode from the equatorial regions due to its high rotational velocity (up to $\sim 75\%$ of the break-up velocity; type II). In Be-star X-ray binaries, the primary star is an early type star in the range $10-20M_\odot$.
Figure 1. Left, model X-ray binaries, based on the Scorpius X-1 binary parameters, showing iso-delay surfaces projected onto the irradiated surfaces of the binary. Right, the associated time delay transfer functions, showing the relative contributions from the regions highlighted in the model X-ray binaries. The accretion disk has constant time delays in the region 0-8 seconds, whereas the time delays from the companion star are seen to vary sinusoidally with binary phase between 0 and 20 seconds. This figure is from O'Brien and Horne (2001).

6.1. Characteristic timescales

Echo mapping has already been developed to interpret lightcurves of Active Galactic Nuclei (AGN, see below), where time delays are used to resolve photoionized emission-line regions near the compact variable source of ionizing radiation in the nucleus. In AGN the timescale of detectable variations is days to weeks, giving a resolution...
in the transfer functions of 1-10 light days (Krolik et al 1991; Horne et al 1991). In X-Ray binaries the binary separation is light seconds rather than light days, requiring high-speed optical/UV and X-ray lightcurves to probe the structure of the components of the binary in detail. The detectable X-ray and optical variations in the lightcurves of such systems are also suitably fast.

In the standard model of reprocessing, X-rays are emitted by material in the deep potential well of the compact object. These photoionize and heat the surrounding regions of gas, which later recombine and cool, producing lower energy photons. The optical emission seen by a distant observer is delayed in time of arrival relative to the X-rays by two mechanisms. The first is a finite reprocessing time for the X-ray photons, and the second is the light travel times between the X-ray source and the reprocessing sites within the binary system.

The light travel times arise from the time of flight differences for photons that are observed directly and those that are reprocessed and re-emitted before travelling to the observer. These delays can be up to twice the binary separation, obtained from Kepler’s third law,

$$\frac{a}{c} = 9.76 \times \left(\frac{M_x + M_d}{\text{msolar}}\right)^{\frac{1}{3}} \left(\frac{P}{\text{days}}\right)^{\frac{1}{3}}$$

(1)

where $a$ is the binary separation, $M_x$ and $M_d$ are the masses of the compact object and donor star, $P$ is the orbital period. In LMXBs the binary separation is of the order of several light seconds.

6.2. Characteristic amplitudes

Examples of both the considerable amplitude of variation seen, and the very bright magnitudes which these sources reach, are provided by V4641Sgr, and by XTE J1118+480.

V4641 Sgr = SAX J1819.3-2525 underwent a bright optical outburst on 1999 Sept. 15.7 UT, going from magnitude 14 to 8.8 in the V-band and $K_s \approx 13$, reaching 12.2 Crab in the X-rays. This outburst was therefore bright, but very brief, with an e-fold decay time of 0.6 days (Figure 2). A radio source was resolved, making of V4641 Sgr a new microquasar (Hjellming et al 2000). The distance of the system is probably between 3 and 8 kpc, with the companion star being a B3-A2 main sequence star. Another possibility is that the companion star is crossing the Hertzsprung gap (type B3-A2 IV), and in this case the distance cited above would be the minimum distance of the system. The system is therefore an Intermediate or High Mass X-ray Binary System (IMXB or HMXB).

The X-ray nova XTE J1118+480 exhibited two outbursts in the early part of 2000. As detected by the Rossi X-ray Timing Explorer (RXTE), the first outburst began in early January and the second began in early March. Routine imaging of the northern sky by the Robotic Optical Transit Search Experiment (ROTSE) shows the optical counterpart to XTE J1118+480 during both outbursts. These data include over 60 epochs from January to June 2000 (Figure 3). A search of the ROTSE data archives reveal no previous optical outbursts of this source in selected data between April 1998 and January 2000. While the X-ray to optical flux ratio of XTE J1118+480 was low during both outbursts, Wren et al (2001) suggest that they were full X-ray novae and not mini-outbursts based on comparison with similar sources. The ROTSE measurements taken during the March 2000 outburst also indicate a rapid rise in the optical flux that preceded the
X-ray emission measured by the RXTE by approximately 10 days. Using these results, Wren et al estimate a pre-outburst accretion disk inner truncation radius of $1.2 \times 10^4$ Schwarzschild radii.

6.3. Milli-Hz Oscillations and QPOs

X-ray pulsar binaries, such as Her X-1, can show optical mHz quasi-periodic oscillations (QPO). In the power spectrum of Her X-1 it appears as ‘peaked noise’, with a coherency $\sim 2$, a central frequency of 35 mHz and a peak-to-peak amplitude of 5%. These QPOs are quite common, and are suggested to have a variety of causes (van der Klis 2000), with mHz oscillations possibly due to warping of the inner accretion disk. In at least some cases, QPO emission probably results from a small hot region, possibly the inner regions of the accretion disk, where the ballistic accretion stream impacts onto the disk.

Intriguingly for the parallel science opportunities for a primarily asteroseismology mission, Wagoner, Silbergleit, and Ortega-Rodriguez (2001) have introduced the analysis concept of ‘Diskoseismology’. They show that one may compare calculations of the frequencies of the fundamental g, c, and p-modes of relativistic thin accretion disks with recent observations of high frequency QPOs in X-ray binaries with black hole candidates. These classes of modes encompass all adiabatic perturbations of such disks. The frequencies of these modes depend mainly on the mass and angular momentum of the black hole; their weak dependence on disk luminosity is also explicitly indicated. Identifying the recently discovered relatively stable QPO pairs with the fundamental g and c modes provides a determination of the mass and angular momentum of the black hole. For GRO J1655-40, these authors derive $M = 5.9 \pm 1.0 M_{\odot}$, $J = (0.917 \pm 0.024) GM^2/c$, in agreement with spectroscopic mass determinations.

7. Active Galactic Nuclei

The ultraviolet and optical continuum and the broad emission line flux of active galaxies are known to be variable on all timescales from hours up to years. Quantification of these variations, both their rate of occurrence and the rate of change, provides direct study of the inner accretion processes around massive black holes. The variations are very broad in frequency, with much of the optical radiation being reprocessed from higher frequencies, as in the accretion stellar systems discussed above. Thus, perhaps the greatest impact of Eddington observations would be in coordination with an extended monitoring program including X-ray and $\gamma$-ray satellites, and ground based spectroscopy. From such studies, reverberation mapping (see the previous section) can determine central black hole masses and accretion rates, and the physical conditions in the accretion disk and line emitting regions. A good review of short-term variability in AGN in general is provided by Wagner & Witzel (1995).

In Seyfert and lower luminosity sources, direct studies of the inner accretion disk are feasible. In a typical model of high-frequency emission (Figure 4), the intrinsic emission originating in the warm skin of the accretion disk is responsible for the spectral component that is dominant in the softest X-ray range. The hard X-ray line emission requires an ionised reflecting medium, perhaps the warm surface of the accretion disk.

![Figure 4. Geometry of the accretion flow in the Narrow line Seyfert I galaxy PG1211+143. The optical flux is emitted by the cold accretion disk ($T \sim 10^4$ K). The disk is the source of seed photons for the hot Comptonizing cloud ($T \sim 10^6$ K, $\tau \sim 20$), which extends below the transition radius $R_{\text{ion}}$. The hard X-ray flux is emitted by the hot flare region ($T \sim 10^9$ K) and is partially reflected by the cloud ($\xi \sim 500$, $\Omega/2\pi \sim 1$). This figure is from Janiuk, Czerny & Madejski 2001).](image)

BL Lac objects, of which a well-studied example is ON 231, have the peak of the synchrotron emission from the core source in the near IR-optical band. Available multi-wavelength monitoring data suggest that the occurrence of a long-term trend in the optical luminosity and of periods of enhanced activity could be related to changes in the innermost radio structure. A better understanding of these phenomenon requires both optical monitoring and VLBI mapping.

Variations on timescales of hours and even less have been observed in AGN. To study the physical processes which are responsible for the observed spectral energy distribution of an active galactic nuclei (AGN) multiwavelength monitoring campaigns have proven to be an excellent tool, (cf. Alloin et al 1994 for an AGN watch overview and Gilmore (1980) for an earlier example). Thus, over the last decade, several large space-based and ground-based monitoring programs have been undertaken for nearby AGN.

Historic light curves of some bright BL Lac objects have shown that fast luminosity fluctuations (typical of this class of AGNs) are frequently superimposed on long-term trends of relatively large amplitude. The origin of these long-term changes is not fully understood. A possibility is that the jet, pointing very close to the observing
Fluxes in broad-band $U, B, V, R$, and $I$ are in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ A$^{-1}$. In the top panel the normalized $V$-band flux of star 0 (+) and C (x) is shown which was constant within $\sim 0.57\%$. (From Dietrich et al, 2001)

Another possible scenario is that of a slowly precessing jet approaching the observer’s line of sight over the past few decades. The progressive increase of the beaming factor would then be responsible for the mean brightening or fading optical trends shown by many BL Lac sources.

Correlation studies of optical outbursts with higher frequency data and radio VLBI maps are required to discern the true evolution of these structures.

7.1. AGN: ARE ANY VISIBLE?

Since AGN are primarily studied at high Galactic latitude, it is necessary to ask if any at all will be visible to a stellar/planetary mission like Eddington. While this is quantified in the next section, an example of what is viable is...
provided by the recent identification of 3EG J2016+3657, an EGRET blazar behind the Galactic Plane.

Halpern et al (2001) recently identified the blazar-like radio source G74.87+1.22 (B2013+370) as the counterpart of a high-energy $\gamma$-ray source in the Galactic plane. However, since most blazar identifications of EGRET sources are only probabilistic in quality even at high Galactic latitude, and since there also exists a population of unidentified Galactic EGRET sources, they obtained additional evidence to support identification of this source as a blazar. Their new observations provide a complete set of classifications for the 14 brightest ROSAT X-ray sources in the relevant error circle (Figure 7), of which B2013+370 remains the most likely source of the $\gamma$-rays. They also obtained further optical photometry of B2013+370 itself which shows that it is variable, providing additional evidence of its blazar nature.

Interestingly, this field contains, in addition to the blazar, the plerionic supernova remnant CTB 87, which is too distant from the field centre to be the EGRET source, and three newly discovered cataclysmic variables, all five of these X-ray sources falling within 16' of each other. This illustrates the very large surface density of astrophysically interesting high-energy sources in the Galactic plane.

8. Supernovae and Gamma-ray bursts

Supernovae are of increasing importance as cosmological probes, as well as continuing of interest as tracers of recent (Type II) and past (Type I) star formation histories, and as the origin of much of the chemical elements. In addition they are of considerable intrinsic interest, as efforts continue to understand the diversity of light curves and rates of different supernova types. At present, there is no reliable ab initio model of a supernova explosion: rather, ‘artificial’ explosions are introduced into the models, with a radial structure adjusted ad hoc to reproduce observed chemical element ratios. Supernova progenitor models remain in need of more direct observational constraints (eg Smartt et al 2001).

One of the key ways in which Eddington will contribute here, and in which no other observational program will be competitive with Eddington results, is in definition of...
the early-time light-curves. It is the structure of the very early light curve which provides clues to the symmetry and (hopefully) mechanism of explosion, crucial information at present completely lacking. Eddington will provide time-resolved photometry during the few hours to few days in which different supernovae brighten, allowing direct tests of the structure of the explosive shocks with observations.

We emphasise that no rapid or special analysis of the data is required, so that there is system impact only on telemetry: supernovae will be detected in the focal plane during normal observations, and can be recovered after the event, provided data are kept.

Two further points are worthy of note. That subset of supernovae, often called hypernovae, which cause gamma-ray bursts, is of especial interest. It remains unknown just what are the statistics of these sources, and what if any intermediate types of these sources exist. Eddington has a less than twenty-percent chance of discovering, and providing full early light-curve data for, such an event, assuming observations in fields where total line of sight extinction is less than a few magnitudes. This does however imply a system impact: the (few known) optical counterparts of gamma-ray bursts are very short-lived, so that the whole focal plane needs to be analysed for sources each time it is read.

8.1. Supernova rates

Present supernova rates are poorly known, while the detectivity will depend on both the Eddington observational mode and the distance from any bright stars. A recent compilation of relevant rate data has been provided by Cappellaro & Turatto (2000). These data (Table 2) show that one supernova occurs per $10^{10} L_{\odot}/B$/100 yr. Thus, an estimate of performance is possible. This unit luminosity is comparable to that of a typical galaxy observed in a magnitude-limited sample. A ‘typical’ supernova is near maximum brightness for about one-month. Thus, one supernova is visible in any month from monitoring of about 1000 galaxies; given a combination of collecting area and field of view which includes 1000 galaxies, one supernova per month will be found. Scaling from extant statistics, Eddington will discover, and provide a complete fully-sampled early light curve for, one supernova for every 30 days of operations, for operation away from the highest extinction lines of sight. We emphasise that no such light curve exists, or is realistically obtainable, at present.

8.2. QSO and Galaxy counts

A key question of course, for supernovae and all extragalactic parallel science, is whether any sources will be visible. Table 3 presents summary QSO and galaxy counts, showing that considerable numbers of galaxies will be in the field of view, except when the primary science field has very high extinction. The QSO counts are taken from Hartwick & Schade (1980), the galaxy counts from Gardner et al (1997). In using this table, it is important to note that the supernovae are (in general) much brighter than the galaxy.

9. Low Surface Brightness Galaxies

Low surface brightness galaxies (LSB) are of considerable intrinsic interest as cosmological and galaxy formation probes. Their existence alone is enough of a puzzle, and they may make up a significant part of all the stars in galaxies. LSB galaxies are hard to detect against the sky brightness. In principle, space observations, where the sky is very much darker, are more sensitive, while the wide field relatively large sky area per pixel of current satellite designs is ideal to detect very low surface brightness sources. However, on current designs, data from Eddington and the related missions is read-noise limited on sky areas. Thus, obtaining very deep observations by stacking data is not possible. But indirect LSB detection, and more generally, detection of any stellar population which does not follow the distribution of high surface brightness galaxies, is certainly possible.

A bonus of the Eddington parallel science is that the fields are chosen for other reasons: thus Eddington will be
sensitive to supernovae in putative Low Surface Brightness galaxies, as well as to field supernovae, if the descendants of the earliest stars (Population Zero) are indeed, as expected in some models, distributed in space more like dark matter than luminous galaxies. Any such discovery, or tight limits, would be valuable. Knowledge of the local mass distribution in the Universe has implications for the peculiar velocity field, the direction and amplitude of the Local Group acceleration, the determination of parameters such as $\Omega_0$ and $H_0$, and on the understanding of the formation and evolution of groups of galaxies (e.g., Peebles 1994).

Is it possible to find such systems, when observations are primarily at low Galactic latitude? Indeed yes, LSB galaxies are already known at very low Galactic latitude.

Dwingeloo 1 (Dw1) is a large SBb/c galaxy, discovered both in a systematic H1 emission survey of the northern part of the Milky Way in search of obscured galaxies in the Zone of Avoidance by Kraan-Korteweg et al. (1994), and independently by Huchtmeier et al. (1995). Interestingly, Dwingeloo 1 is known to contain a bright X-ray source (Reynolds et al. 1997), arguably a SuperEddington Source (sic), as luminous as a 10 M$_\odot$ black hole accreting at close to its Eddington limit; however, the nature of these super-Eddington sources remains unclear. An optical counterpart to the super-Eddington X-ray source, NGC 5204 X-1 has been recently suggested, confirming the need for continuing optical studies of these sources and these galaxies.

10. Gravitational Lensing

10.1. Microlensing

Gravitational microlensing of background stars in the Galactic bulge by foreground stars in the Galactic disk is a rare phenomenon. Nonetheless, it happens, and is observed. The characteristic microlensing signals are the light curve, lack of colour variability, and photometric stability outside the lensing event. This requires photometry over longer timescales than are appropriate for the present proposed missions, and multi-colour data. For planet finding missions, microlensing will be a noise source rather than a signal.

One possibly interesting application where planet searching modes can study microlensing directly, is in pixel microlensing. This method considers fluctuations in the integrated light from all the unresolved stars in a pixel. A critical requirement is point spread function (psf) and pointing stability, maximising comparison of like with like data. If there is an unresolved background galaxy in any field, pixel microlensing will be a sensitive opportunity, given the psf stability, which vastly exceeds that available from the ground, so long as the spacecraft jitter is small (cf Calchi Novati et al 2001).

10.2. Macrolensing

Gravitational macro-lensed systems, such as the famous ‘Einstein Cross’, are known and are variable. Analysis of the variability delays between the image components can be of profound significance for cosmological studies. However, the complexity of the image structure, together with the natural several-year timescales, and the rareness of such systems, precludes this as a major contribution of the present missions.

11. Conclusions

Asteroseismology and planet transit searching necessarily produce high-quality time-series photometry for the primary target stars. Where system considerations allow, the equally high-quality photometry for other objects in the field of view can provide excellent science in many fields. Some of the most obvious are noted here.

While direct star-count studies of Galactic structure are not an ideal parallel science priority, we also recall however the recent substantial advances in mapping phase-space substructures in the outer Galactic halo which followed identification of a large sample of faint RRLyrae stars (eg Vivas et al, 2001). The significance of pulsating variables as distance indicators, RR Lyraes for old stellar populations, Cepheids for young populations, and the relevance of those distances for studies of galactic structure, is worth consideration.
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