New Astrophysical Opportunities Exploiting Spatio-Temporal Optical Correlations

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Abstract. The space-time correlations of streams of photons can provide fundamentally new channels of information about the Universe. Today's astronomical observations essentially measure certain amplitude coherence functions produced by a source. The spatial correlations of wave fields has traditionally been exploited in Michelson-style amplitude interferometry. However the technology of the past was largely incapable of fine timing resolution and recording multiple beams. When time and space correlations are combined it is possible to achieve spectacular measurements that are impossible by any other means. Stellar intensity interferometry (*SII*) is ripe for development and is one of the few unexploited mechanisms to obtain potentially revolutionary new information in astronomy. As we discuss below, the modern use of *SII* can yield unprecedented measures of stellar diameters, binary stars, distance measures including Cepheids, rapidly rotating stars, pulsating stars, and short-time scale fluctuations that have never been measured before.

1. Introduction

More than 40 years ago the basic principles of *intensity interferometry* were developed and proven through the measurement of stellar diameters with sub-milli-arcsecond resolution [1, 2]. Yet this breakthrough ran its course due to technological limitations. The old technology was limited to two telescope beams, and integration of correlations was done by the elegantly primitive device of counting the turns of an electric motor. In the interim the technology of photon detection has exploded, and the ability to handle and correlate multiple beams with exquisite time resolution has been perfected. It is hard to overstate the advantages now possible with current and future detection technology, both in real-time and off-line, both with simple pairs and with multiple detector arrays.

SII works by comparing the random intensity fluctuations of light waves entering separated detectors. Nothing special is needed from the source, and black-body, thermal correlations are ideal. While quantum properties derived from the statistics of photon arrival times (e.g. photon bunching behavior) add extra information, the effect is robust, and works whether or not quanta are well-resolved. Statistical correlations of beams of a given wavelength λ separated by a given distance D allows resolution of structure at the Rayleigh criterion $\Delta\theta \sim \lambda/D$. This is how measurements equivalent to 100 meter telescopes were made with *SII* 40 years ago [3]. The exacting match of optical path lengths needed in amplitude (Michelson) interferometry is completely unnecessary, because different phase properties dominate *SII*. Troublesome sensitivity to path length differences caused by atmospheric turbulence is completely eliminated for the same reason. Vast quantities of photons are however required and the visual wavelength region is most appropriate. Several algorithms are available for phase recovery in a multi-beam set-up, permitting model independent imaging [4, 5]. Current detection technology allow therefore a revolution in SII: multiple telescope, long baseline optical *intensity interferometry*. A system can be devised [6, 7] that would consist of hundreds of large flux gathering surfaces spread out over kilometers of baseline that would enable to make the next big step in astronomy: optical imaging at μ-arcsecond resolution.

2. Astrophysical applications for μ-arcsecond imaging SII

Properly imaging stellar surfaces constitutes a major break-through in stellar astrophysics. Stars have angular sizes of tens of milli-arcseconds or less, and until now, apart from the sun, only Betelgeuse and Altair have been imaged albeit with a modest number of resolution elements (at maximum ten). Technical requirements for SII are such that one can easily be looking at hundred resolution elements with an order of magnitude increase in angular resolution. Stellar physics has been waiting for a long time to make this leap forward, and it is similar to the impact realized by Hanbury Brown and Twiss when they measured 32 stellar diameters with the first and only application of SII in astronomy [3]. Modern SII would undoubtedly extend solar physics to the realm of the stars. Moreover, feasibility studies indicate that SII may not be limited to resolving Galactic sources only. We present therefore an overview of core galactic and extra-galactic science drivers:

- Stellar surface phenomena and dynamo action
- Conditions for planet formation around young stars
- Cepheid properties and the distance scale
- Mass loss and fast rotation of massive hot stars and supernova progenitors
- Nuclear optical emission from AGN
- Structure of gamma-ray bursts

Of course, feasibility of these science topics depends on the design of the intensity interferometer. For practical purposes we adopt a conservative limiting visual magnitude $\mathrm{m_v} < 8^{\mathrm{m}}$ and a resolution of a 0.1 milli-arcsecond, and we detail the science that would be opened up within these limits.

Stellar surface phenomena, star formation and binaries Pre-main sequence (PMS) objects are young stars that are contracting towards the main-sequence, still lacking internal hydrogen combustion. Key questions relating to the physics of mass accretion and PMS evolution can be addressed by means of very high resolution imaging. Spatially resolved studies would involve the absolute calibration of PMS tracks, the mass accretion process, continuum emission variability, and stellar magnetic activity. The technique may allow spot features on the stellar surface to be resolved. Hot spots deliver direct information regarding the accretion of material onto the stellar surface. Cool spots, on the other hand, may cover 50% of the stellar surface, and they are the product of the slowly decaying rapid rotation of young stars. Imaging them will constrain the interplay of rotation, convection, and chromospheric activity as traced by cool spots and need not be limited to PMS stars only. It may also provide direct practical application as the explanation for the anomalous photometry observed in young stars [10].

In the last decade several young coeval stellar groups have been discovered in close proximity ($\sim$50 pc) to the sun. Famous examples are the TW Hydra and β Pic comoving groups. The majority of the spectral types within reach range between A and G-type, and about 50 young stars have $\mathrm{m_v} < 8^{\mathrm{m}}$. Their ages lie within the range 8 to 50 Myr (see [11] for an overview). The age intervals ensures that a substantial fraction of the low-mass members are still in their PMS contraction phase. Key targets for calibration of evolutionary PMS tracks in the Hertzsprung-Russell diagram are spectroscopic binaries. Resolving binaries delivers the inclination of the system and hence access to the mass of the components. This is a

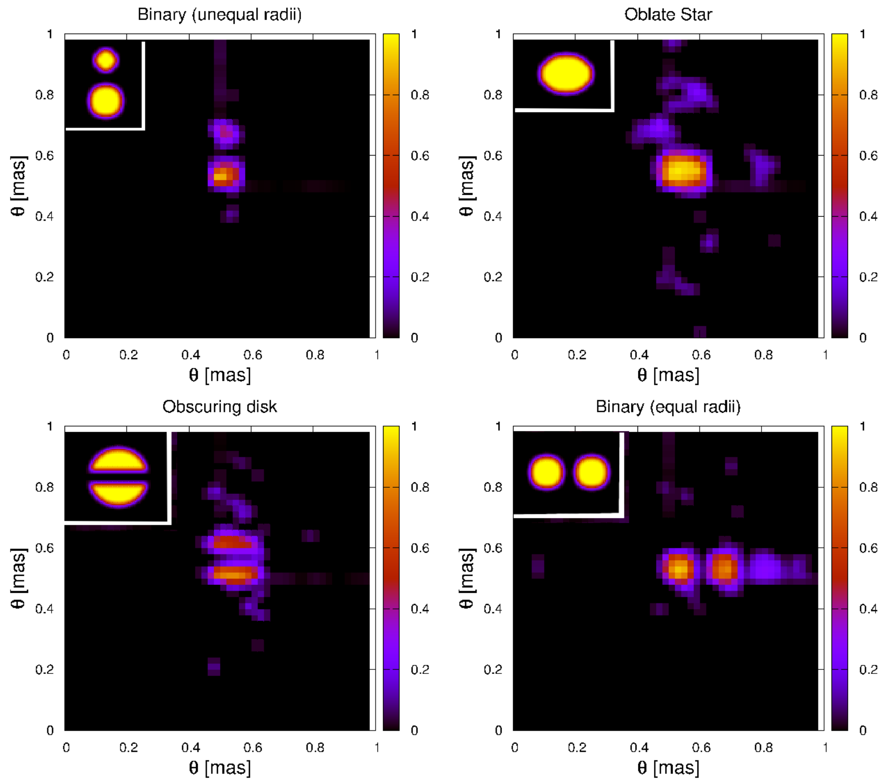

Figure 1. Four examples of images reconstructed from *SII* data as would be recorded with an array that operates at a wavelength of $\sim 400\,\mathrm{nm}$ with one hundred telescopes and a telescope separation of $\sim 100\,\mathrm{m}$. The pristine image is shown at the top left in each example. The images were produced [8] using an algorithm based on the Cauchy-Riemann equations [9]. The analysis does not yet include a realistic noise component, which is still actively being investigated.

fundamental exercise not only for PMS stars but for all spectroscopic binaries in any evolutionary stage. Measurement of angular sizes of individual PMS stars in combination with a distance estimate (e.g. GAIA) allows a direct comparison between predicted and observed sizes of these gravitationally contracting stars. The proximity of the comoving groups ensures that their members are bright. Their proximity renders the comoving group also relatively sparse making them very suitable, unconfused targets. The sparseness is also the reason for incomplete group memberships, making it likely that the number of young stars close to the sun will increase with the years to come.

Distance scale and pulsating stars Measuring diameters of Cepheids is a basic method with far reaching implications for the calibration of the distance scale. A radius estimate of a Cepheid can be obtained using the Baade-Wesselink method. The Baade-Wesselink method relies on the measurement of the ratio of the star size at times t_1 and t_2, based on the luminosity and color. Combined with a simultaneous measurement of the radial velocity, this method delivers the difference in the radius between t_1 and t_2. With the known difference and ratio of the radius at two times, one can derive the radius of the Cepheid. Combining *SII* angular size measurement with the radius estimate one obtains the distance (see [12]). This makes possible the calibration of the all important Cepheid period-luminosity relation using local Cepheids. Nearly all of the *Hipparcos* distances for Cepheids have rather large trigonometric errors (see [13]) giving rise to ambiguous results. A count of Cepheids observed with *Hipparcos* [14] shows that at least 60 Cepheids are visually brighter than 8^m.

Rapidly rotating stars and hot stars As a group, classical Be stars are particularly well-known for their close to break-up rotational velocities as deduced from photospheric absorption lines. In addition the stars show Balmer line emission firmly established as due to gaseous circumstellar disks, that appear and disappear on timescales of months to years. Photometric observations of Be star disks seem to indicate that they may actually evolve into ring structures before disappearing into the interstellar medium (e.g. [15]). These two phenomena (rapid rotation and circumstellar disks) are somehow related, but many open questions exist regarding the detailed physical processes at play. The Be-phenomenon is important given the large number of stars and fundamental stellar physics involved (fraction of Be stars to normal B-type peaks at nearly 50% for B0 stars, [16]). Absorption line studies cannot provide the final answer to their actual rotational velocity due to strong gravity darkening at the equator and brightening at the pole areas. Direct measurement of the shape of the rotating star is not hampered by gravity darkening, and can provide a direct indication of the rotational speed (see α Eri with the VLTI, [17]). The disk's Bremsstrahlung can constitute $\sim 30\%$ of the total light in V-band [16]. There are about 300 Be stars[1] brighter than $\mathrm{m_v} = 8^{\mathrm{m}}$, roughly corresponding to a distance limit of 700 pc.

The signal-to-noise ratio of an optical intensity interferometer improves with the temperature of the target. Since SII is insensitive to atmospheric turbulence, observations in the violet or blue pose no problem. Eliminating the "Achilles' Heel" of standard phase interferometry will enable high resolution studies of hot stars over very long geometric baselines. A rough estimate of the effective temperatures of the objects in the Bright Star Catalog reveals that approximately 2600 stars brighter than visual magnitude 7 and hotter than 9000 K exist in the sky, all of which should be realistic targets even for a fairly modest intensity interferometer. Typical angular sizes for the stellar surface disk range between 0.5 and 5 mas. Of these targets, a handful of especially interesting ones are presented below, along with some brief notes on their possible science potential.

- **Rigel (β Orionis)** Rigel is the nearest blue supergiant (240 pc). It is a very dynamic object with variable absorption/emission lines and oscillations on many different timescales - from minutes to weeks [18]. The physical properties of Rigel have recently been shown to be very similar to the supernova progenitor SN1987A. This realization makes understanding the dynamical nature of Rigel highly relevant.
- **β Centauri** β Centauri is a binary system consisting of two very hot, very massive variable stars. Both components are variable both spatially and in their line profiles. The intricate nature of the system has led to it being called "a challenge for current evolution scenarios in close binaries" [19].
- **Vega (α Lyrae)** While one of the most fundamental stars in the sky for calibration purposes, the nature of Vega has proven to be more complicated than previously thought. Recent phase interferometry studies suggest an 18-fold drop in intensity at 500 nm from center to limb, consistent with a rapidly rotating pole-on model, as contrasted to the 5-fold drop predicted by non-rotating models [20]. Intensity interferometry will direct studies of the intensity distribution at shorter wavelengths and in different passbands. Such observations will lead to a better understanding between the link between rotation and limb darkening in different wavelength regions.
- **η Carinae** η Carinae is the most luminous star known in the Galaxy, and an extremely unstable and complex object. Recent VLTI studies have revealed asymmetries in the stellar

[1] `http://www.astrosurf.com/buil/us/becat.htm`

winds due to the rapid rotation of the star [21]. Like Rigel, η Carinae is believed to be on the verge of exploding as a core-collapse supernova.

- γ^2 **Velorum** γ^2 Velorum is a binary consisting of a hot O-type star and a Wolf-Rayet star. The proximity to the O-type star creates a situation where two stellar winds interact, creating a wealth of interesting phenomena such as wind collision zones, wind-blown cavities and eclipses of spectral lines [22]. The bright emission lines of WR stars make them suitable for comparative studies in different passbands, as discussed above.

Optical emission from AGN Nuclear optical continuum emission from AGN is visible whenever there is a direct view of the accretion disc (although jets can also contribute to this component). NGC 1068 is among the brightest and the most nearby active galaxy (18.5 Mpc), and hence the prototypical AGN. The core of the galaxy is very luminous not only in the optical, but also in ultraviolet and X-rays, and a supermassive black hole is required to account for the nuclear activity. The VLTI has succeeded in resolving structures in the AGN torus at mid-infrared wavelengths [23] on scales of 30 milli-arcsecond. On the other hand, the blue optical continuum emission is dominated by thermal emission from the inner accretion disk (the source of the "big blue bump" in many quasars) and much more compact. The optical emission regions have an expected size of 0.3 milli-arcsecond at the distance of NGC 1068 and resolving it would be a fantastic achievement. The nucleus has a visual magnitude of around 10^{m}.

Gamma-ray bursts and supernovae The energy, spectrum and delay between the spectrally-remote events and their inexplicable energy have long been puzzling. Initial models assumed clashes between expanding shells to explain these bright events [24], and later concentrated on polar shells. Another model tried to explain the effect by assuming relativistic plasma spheres in which directionality sets all these observed parameters [25]. Resolution is required to decide between the many models for these hot spots. The currently available high-spatial resolution instruments are all insufficient as amplitude interferometers cannot operate on long enough baselines in the crucial blue and ultraviolet regime [27]. Early warning systems will allow to obtain some spatial and spectral information at the peak of the optical flux. Since most of these events are extremely far, we can expect only those within z= 1 to be resolvable. There have been at least two such bright ($\mathrm{m_v} < 9^{\mathrm{m}}$) objects, GRB990123 and GRB080319B, and there are others (e.g. GRB050509B) with host galaxies, all of which are of interest.

3. Cherenkov telescope arrays as an optical intensity interferometer

The major observational advantages of an intensity interferometer are its low requirements on path length equalization and its relative insensitivity to atmospheric seeing. However traditional implementation has required huge quantities of light. Cherenkov telescopes are capable of gathering huge quantities of light and recent studies [28] have rediscovered the potential of the next-generation Imaging Air Cherenkov Telescope (IACT) arrays as a multi-element intensity interferometer. Two major IACT array facilities for γ-ray astronomy are currently under design-study: the Advanced Gamma Imaging System (AGIS [29]) in the US and the Cherenkov Telescope Array (CTA [30]) in Europe. Current designs will offer several thousand baselines (tens to a hundred telescopes) from a few tens of meters to more than a kilometer (Figure 2) and would achieve a limiting magnitude for SII of $\mathrm{m_v} \approx 9^{\mathrm{m}}$, achievable within a few hours exposure [28, 31, 32]. CTA is on the roadmap[2] of the European Strategy Forum on Research Infrastructures (ESFRI), is stated as one of the "Magnificent Seven" of the European strategy for astroparticle physics published by ASPERA[3] and is highly ranked in the strategic plan for

[2] ftp://ftp.cordis.europa.eu/pub/esfri/docs/esfri_roadmap_update_2008.pdf

[3] http://www.aspera-eu.org/images/stories/roadmap/aspera_roadmap.pdf

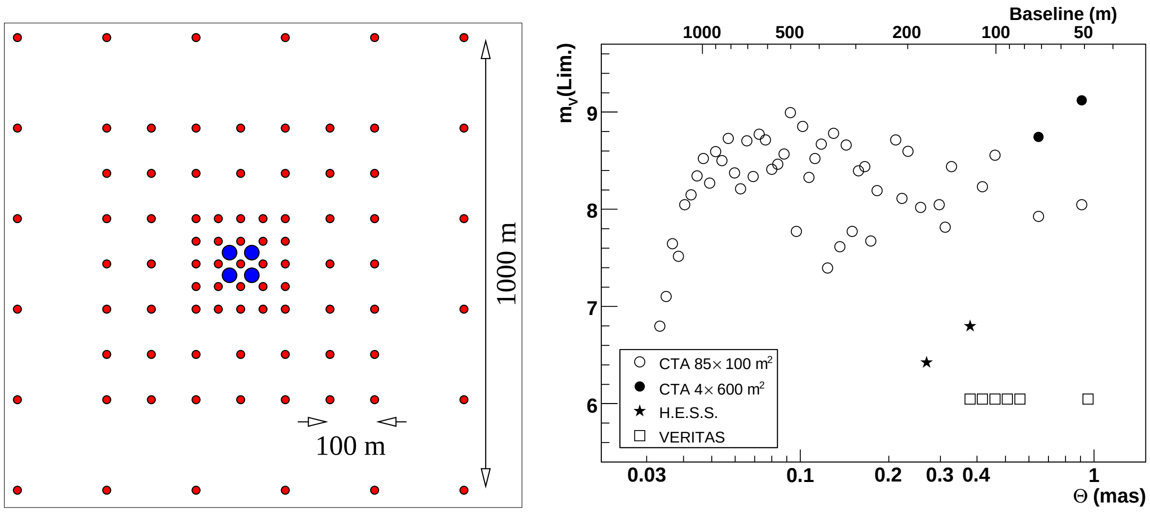

Figure 2. *Left:* Proposed lay-out for the future CTA. Small red dots are the 85 100 m^2 dishes, large blue dots are the four 600 m^2 dishes (adapted from [26]). *Right:* Limiting optical magnitude estimate as function of baseline for a 5σ detection, in a 5 hr integration on a centro-symmetric object with 50% visibility. Sensitivity for SII of current ground-based γ-ray facilities (HESS, and VERITAS) are also included. Final limiting magnitudes depend on signal bandwidth and CTA design details, see [28].

European astronomy of ASTRONET[4]. The AGIS collaboration has provided a white paper for the Division of Astrophysics of the American Physical Society on the status and future of ground-based TeV γ-ray astronomy [33]. The next generation of IACT arrays are foreseen to come on-line within the next 10 years. Implementation of SII with IACT arrays will result in imaging capabilities with an expected angular resolution of 0.05 mas at 400 nm.

IACT γ-ray observations are done with a low duty cycle due to a requirement for low night-sky background light levels excluding moonlight.Meanwhile SII observations in narrow optical bands are much less affected by the background The SII exploitation of large IACT arrays will close to double their operational duty cycle for a modest additional cost. The elegant combination of $SII - IACT$ will increase and diversify science output by giving access to unprecedented imaging capabilities.

These new developments across the community have resulted in the formation of a working group on the topic within the IAU commission 54 on optical and infrared interferometry[5]. The group met officially for the first time during a workshop in January 2009[6]. A report for the CTA collaboration is in preparation. Provisions will be included in the high energy γ-ray camera design to make the future installation of SII specific hardware possible. The foreseen IACT arrays offer a sufficiently dense coverage of the Fourier plane to perform actual image reconstruction. Implementation of SII on IACT arrays is identified as a natural first step towards revival of intensity interferometry.

4. Concluding remarks

The natural synergy of IACT arrays and SII will bring together disparate research communities around a single large scale facility with imaging capabilities at an unprecedented angular

[4] http://www.astronet-eu.org/
[5] http://physics.technion.ac.il/~intint/index.html
[6] http://www.physics.utah.edu/~lebohec/SIIWGWS/

resolution. This will usher in true imaging of diverse stellar phenomena such as rapidly rotating stars and mass accretion processes. It will illuminate stellar evolution processes through calibration of pre-main sequence tracks and highly evolved systems close to going supernova. It will significantly improve the distance scale by calibrating the Cepheid period-luminosity relation. Extra-galactic targets are fainter and smaller, but not out of reach of future IACTs. The time for revival of intensity interferometry in astronomy has arrived.

The temporal variant of SII has been chosen for a planned quantum optics instrument for the European Extremely Large Telescope, and is in an advanced stage of development. *Quanteye* is designed to perform on sub-nanoseconds time scales allowing photon correlation spectroscopy[34, 35, 36, 37]. It will provide new insights into high-speed astrophysical phenomena and the fine structure of photon emission. As astronomy is ultimately driven by technical innovation rather than theoretical predictions, these and other related developments of intensity interferometry will undoubtedly open up a new vantage point on the universe.

References

[1] Hanbury Brown R and Twiss R Q 1956 *Nature* **178** 1046
[2] Hanbury Brown R and Twiss R Q 1958 *Royal Society of London Proceedings Series A* **248** 199
[3] Hanbury Brown R, Davis J and Allen L R 1974 *MNRAS* **167** 121
[4] Sato T, Wadaka S, Yamamoto J and Ishii J 1978 *Appl. Opt.* **17** 2047
[5] Vildanov R R, Ismatov M S, Kodirov N Z, et al. 1998 *Turkish Journal of Physics* **22** 949
[6] Ofir A and Ribak E N 2006 *MNRAS* **368** 1652
[7] Ofir A and Ribak E N 2006 *MNRAS* **368** 1646
[8] Nunez P, Le Bohec S, et al. 2009 in prep.
[9] Holmes R B and Belen'kii M S 2004 *Journal of the Optical Society of America A* **21** 697
[10] Stauffer J R, Jones B F, Backman D, et al. 2003 *AJ* **126** 833
[11] Zuckerman B and Song I 2004 *ARA&A* **42** 685
[12] Sasselov D and Karovska M 1994 *ApJ* **432** 367
[13] Feast M W and Catchpole R M 1997 *MNRAS* **286** L1
[14] Groenewegen M A T 1999 *A&AS* **139** 245
[15] de Wit W J, Lamers H J G L M, Marquette J B, et al. 2006 *A&A* **456** 1027
[16] Zorec J and Briot D 1997 *A&A* **318** 443
[17] Domiciano de Souza A, Kervella P, Jankov S, et al. 2003 *A&A* **407** L47
[18] Stewart H A, Guinan E F, Wasatonic R, et al. 2009 in *American Astronomical Society Meeting Abstracts* **213** 408
[19] Ausseloos M, Aerts C, Uytterhoeven K, et al. 2002 *A&A* **384** 209
[20] Peterson D M, Hummel C A, Pauls T A, et al. 2006 *Nature* **440** 896
[21] Weigelt G, Kraus S, Driebe T, et al. 2007 *A&A* **464** 87
[22] Millour F, Petrov R G, Chesneau O, et al. 2007 *A&A* **464** 107
[23] Jaffe W, Meisenheimer K, Röttgering H J A, et al. 2004 *Nature* **429** 47
[24] Sari R, Piran T and Narayan R 1998 *ApJ* **497** L17
[25] Dado S, Dar A and De Rújula A 2003 *A&A* **401** 243
[26] Bernlöhr K *et al.* 2007 *Proc. International Cosmic Ray Conference*
[27] Bloom J S, Perley D A, Li W, et al. 2009 *ApJ* **691** 723
[28] Le Bohec S and Holder J 2006 *ApJ* **649** 399
[29] AGIS, 2008, http://www.agis-observatory.org
[30] CTA, 2008, http://www.mpi-hd.mpg.de/hfm/CTA/
[31] Le Bohec S, Daniel M, de Wit W J, et al. 2008 in *American Institute of Physics Conference Series* **984**, 205
[32] Le Bohec S, Barbieri C, de Wit W J, et al. 2008 in *SPIE Conference Series* **7013**
[33] Buckley J, Byrum K, Dingus B, et al. 2008 *ArXiv e-prints 0810.0444*
[34] Barbieri C, da Deppo V, D'Onofrio M, Dravins D, et al. 2006 in *IAU Symposium* **232**, 506
[35] Naletto G, Barbieri C, Dravins D, et al. 2006 in *SPIE Conference Series* **6269**
[36] Barbieri C, Naletto G, Occhipinti T, et al. 2007 *Memorie della Societa Astronomica Italiana Supplement* **11** 190
[37] Dravins D, Barbieri C, Fosbury R A E, et al. 2006 in *IAU Symposium* **232**, 502