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Light Echoes

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Abstract. The first "light echo"—scattered light from a stellar outburst arriving at the Earth months or years after the direct light from the event—was detected more than 100 years ago, around Nova Persei 1901. Renewed interest in light echoes has come from the spectacular echo around V838 Monocerotis, and from discoveries of light echoes from historical and prehistorical supernovæ in the Milky Way and Large Magellanic Cloud as well as from the 19th-century Great Eruption of η Carinae. A related technique is reverberation mapping of active galactic nuclei. This report of a workshop on Light Echoes gives an introduction to light echoes, and summarizes presentations on discoveries of light echoes from historical and prehistorical events, light and shadow echoes around R CrB stars, and reverberation mapping.

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1. Introduction to the Workshop

The phenomenon of a light echo occurs when light from a transient event, such as a supernova or other eruptive stellar outburst, scatters off nearby dust and reaches the Earth at later times than the light from the event itself. The first light echo was seen over a century ago, following the outburst of Nova Persei 1901. The apparent superluminal motion of these echoes excited considerable interest among astronomers at the time, but the subject then sank into relative obscurity. However, light echoes have recently received renewed interest because of the spectacular echo around V838 Monocerotis (which produced iconic *Hubble Space Telescope* images), and the interstellar and circumstellar echoes around SN 1987A.

Recently, there have been remarkable discoveries of light echoes from ancient supernovæ and other luminous transients in the Magellanic Clouds and Milky Way, allowing spectroscopic observations with modern equipment of events that occurred centuries ago. In extragalactic astronomy, "reverberation mapping" is a closely related technique used to study the structure of active galactic nuclei.

A 90-minute Workshop on the topic of "light echoes" was held during the Symposium. There were four semi-formal presentations, as described below, along with question-and-answer sessions and general discussion.

2. Light Echoes (H.E. Bond)

There are three requirements to produce an observable light echo:
(1) there must be an illuminating star that varies rapidly in brightness;
(2) the star must be intrinsically luminous (typically a nova or supernova); and
(3) there must be circumstellar or interstellar dust in the vicinity of the variable star.

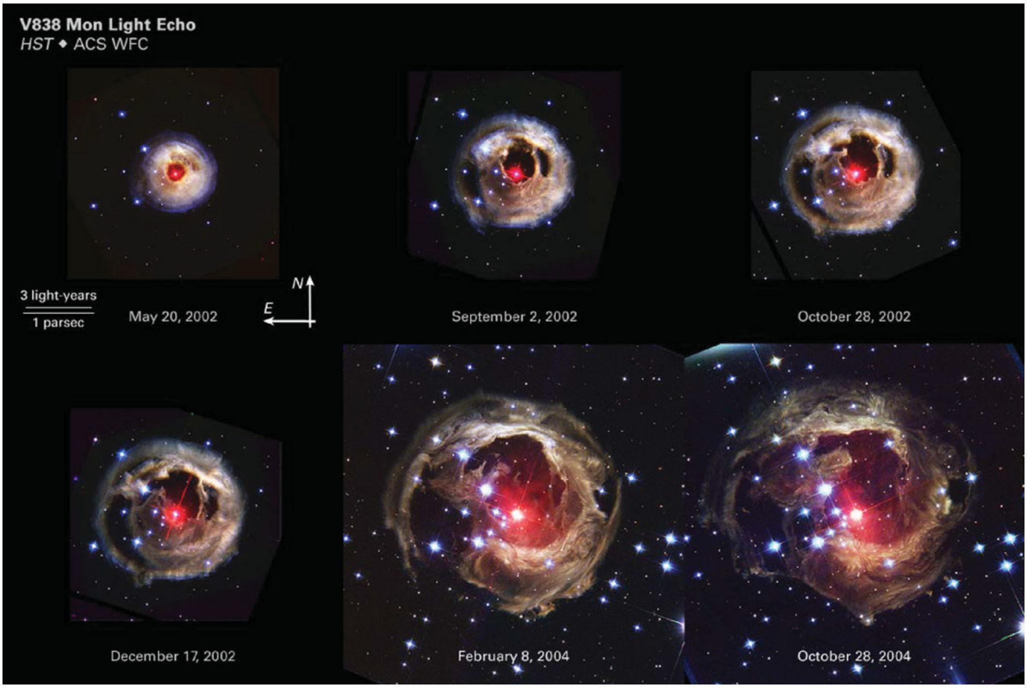

Figure 1. *Hubble Space Telescope* images showing the evolution and apparent superluminal expansion of the light echoes around V838 Mon. The images were obtained with the Advanced Camera for Surveys, and are all at the same angular scale.

It is extremely rare for all three requirements to be satisfied simultaneously, and thus light echoes have historically been detected only rarely.

The geometry of a light echo is simple (Bond *et al.* 2003, and references therein): at a time t after the outburst, the illuminated dust lies on the paraboloid given by $z = x^2/2ct - ct/2$, where x is the projected distance from the star in the plane of the sky, z is the distance from this plane along the line of sight toward the Earth, and c is the speed of light. This geometry explains why it is typically possible for an echo to appear to expand at many times the speed of light, when there is illuminated material well in front of the star.

The eruption of the previously unknown variable star V838 Monocerotis in 2002 produced the most spectacular light echo of modern times (see Fig. 1 for examples of *HST* images). The star itself belongs to a newly recognized class of "intermediate-luminosity red transients" or "luminous red novæ," whose maximum luminosities lie between those of classical novæ and supernovæ (see Bond *et al.* 2009). They generally evolve to extremely cool temperatures as their outbursts proceed. V838 Mon itself evolved from a K spectrum, through type M, and eventually was classified as the only known L-type supergiant.

Because of the superluminal expansion, direct images of light echoes are incapable of providing a geometric distance to the illuminating star. However, it is possible to use polarimetric imaging to identify highly linearly polarized locations within the echo, at which the scattering angle is close to 90°; in this case, the above equation, with z set to zero, shows that the x distance is simply ct, and thus the angular radius yields a geometric distance. This novel method of astronomical distance determination was proposed by Sparks (1994), and applied with success to the V838 Mon echo by Sparks *et al.* (2008), based on polarimetric imaging with the *HST* Advanced Camera.

In the case of a periodic luminous variable star surrounded by a reflection nebula, there will be a train of nested light echoes propagating away from the star. The luminous Galactic Cepheid variable RS Puppis (with a 41.4-day period) provides a spectacular example of these nested echoes (Kervella *et al.* 2008). We are currently analyzing *HST* polarimetric imaging of the RS Pup nebula in order to determine a geometric distance to this important Cepheid (see Bond & Sparks 2009 for an outline of the method).

3. Light Echoes from Historical and Prehistorical Events (A. Rest)

In the last few years, the technique of difference-imaging of fields adjacent to known luminous transients has been exploited to make a number of discoveries of light echoes.

Among the most spectacular results have been the detection of a light echo from the 19th-century Great Eruption of η Carinae, allowing us to obtain the first spectroscopic observations of the star during this cataclysmic event (Rest *et al.* 2012). We have also discovered echoes from, and obtained spectra of, such historical events as the Cas A and Tycho supernovæ (Rest *et al.* 2008a, 2011). Moreover, we have detected light echoes from previously unknown supernovæ in the Large Magellanic Cloud, most of which can be associated with known young SN remnants in the LMC (Rest *et al.* 2008b).

One exciting application of the use of light echoes, permitted by the spectroscopic observations of supernovæ, is the possibility of seeing the event from several different viewing angles. As an example, this has allowed the discovery of anisotropic ejection in the case of the Cas A supernova (Rest *et al.* 2011).

4. Light and Shadow Echoes around R CrB stars (G. Clayton)

R Coronae Borealis (RCB) stars are luminous, hydrogen-deficient, carbon-rich supergiants (Clayton 1996; also p. 125). Two leading evolutionary models for producing these objects are a merger of a double white dwarf, and a final helium shell flash in a (single) star at the top of the white-dwarf cooling track, following ejection of a planetary nebula.

We obtained *HST*/ACS images of the reflection nebula surrounding the RCB star UW Cen in 2004 (see Clayton 2005). This nebula, first detected in 1990, is the only known reflection nebula around an RCB star. It has changed its appearance significantly since discovery.

At the estimated distance of UW Cen, the reflection nebula is approximately 0.6 light years in radius, so the nebula cannot have physically altered in such a short time. Instead, the morphology of the nebula appears to change as different parts are illuminated by light from the central star, modulated by shifting thick dust clouds near its surface. These dust clouds form and dissipate at irregular intervals, causing the well-known declines in the RCB stars. In that way, the central star acts like a lighthouse shining through holes in the dust clouds and illuminating different portions of the nebula.

When new dust forms, a “shadow echo” can be seen to move out from the star through the nebula. The existence of this nebula provides clues to the evolutionary history of RCB stars, specifically providing a possible link between them and planetary nebulæ; this would support the final helium shell flash model.

5. Reverberation Mapping of Active Galactic Nuclei (M.C. Bentz)

Active galactic nuclei (AGNs) are some of the most energetic objects in the universe, but are difficult to study in detail because of their large distances. The compact inner region of photoionized gas in an AGN only spans micro-arcseconds in angular size, and is spatially unresolvable for the forseeable future. Reverberation mapping (Blandford & McKee 1982; Peterson 1993) has therefore become the most useful tool for probing AGN structure because it can take advantage of their flux variability and, in effect, substitute time resolution for spatial resolution.

The basic technique involves monitoring an AGN spectroscopically over a period of several weeks to months or years. The continuum flux in an AGN is produced near the central black hole (BH) (probably in the surrounding accretion disk) and has been observed to vary on time-scales of hours to days. The gas in the photoionized broad-emission-line region (BLR) responds to the continuum variations with a time delay τ, the magnitude of which varies directly with the luminosity state of the AGN.

The average time delay between continuum fluctuations and the response of a broad emission line gives a measurement of the average size of the emission-line region. Combining τ with the velocity-broadened width of the emission line through the virial theorem provides a direct gravitational probe of the mass of the central supermassive BH. To date, some 50 BH masses have been determined in this way (Peterson *et al.* 2004; Bentz *et al.* 2009) and provide the basis for *all* BH mass determinations in AGNs at cosmological distances.

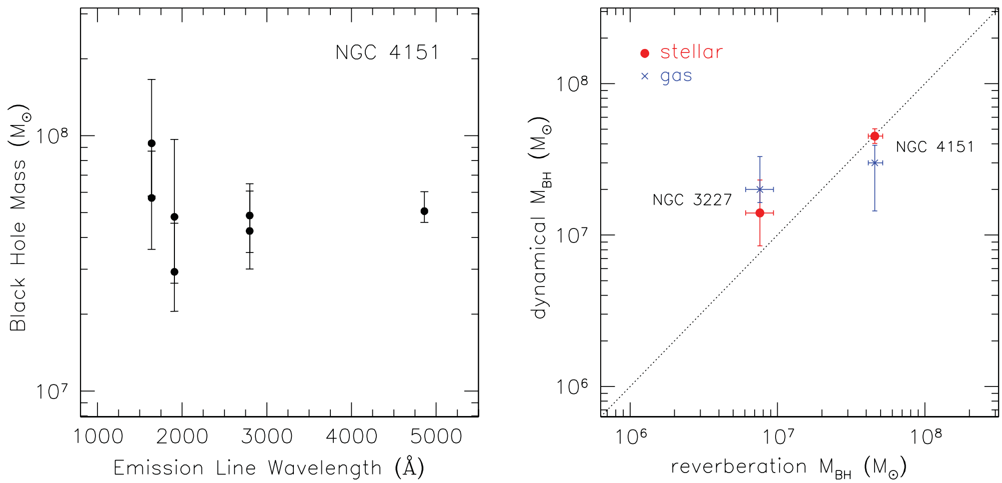

Figure 2. *Left:* Black-hole masses for NGC 4151 derived from reverberation mapping of several optical (Bentz *et al.* 2006) and UV (Metzroth *et al.* 2006) broad emission lines, all of which show a general consistency. *Right:* Reverberation masses for NGC 3227 and NGC 4151, compared to the masses derived from stellar dynamical modelling (circles) and gas-dynamical modelling (crosses) of spatially-resolved observations of the centres of these galaxies. The dotted line is the line of equality.

Several independent lines of argument provide evidence that reverberation measurements yield reliable measurements of the central BH mass. The BLR has been observed to exhibit ionization stratification, in which the more highly ionized emission lines (such as He II and C IV) respond to continuum variations with shorter time delays than the Balmer lines (Peterson 2001; Bentz *et al.* 2010a). The widths of these more highly ionized emission lines are broader and follow the expected $V \propto \tau^{1/2}$ relationship for gas

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undergoing gravitationally dominated motion, resulting in a constant BH mass determination from multiple emission lines (Peterson & Wandel 2000; Kollatschny 2003; Bentz *et al.* 2010a; see Fig. 2). Furthermore, although reverberation masses currently rely on a scaling factor that is derived by assuming that all galaxies follow the same $M_{\rm BH} - \sigma_\star$ relationship (Onken *et al.* 2004; Woo *et al.* 2010), it has been possible to determine the BH masses of two AGNs independently through dynamical modelling.

The results of both gas-dynamical and stellar-dynamical modelling from spatially resolved observations of the centers of NGC 4151 and NGC 3227 give dynamical masses that are consistent with the masses derived from reverberation mapping (Davies *et al.* 2006; Onken *et al.* 2007; Hicks & Malkan 2008; see Fig. 2). A search is currently underway to identify additional candidates for such studies.

Reverberation mapping has the potential to map out directly the response of the gas in the BLR as a function of time delay and velocity, thereby providing direct observational constraints on the geometry and kinematics of the BLR gas. Recent spectroscopic monitoring campaigns have begun to achieve the data quality necessary to carry out a full decomposition of the line response (Bentz et al. 2010b), and a substantial amount of effort is currently being invested in carrying these analyses further and in obtaining additional high-quality monitoring datasets.

As our observational strategy and analysis methods continue to improve, reverberation mapping has to potential to provide, among other things, a solid foundation for the determination of BH masses in galaxies at cosmological distances. The observed tight correlations between host-galaxy properties and central BH masses imply that BHs strongly influence their host galaxies. By understanding the masses of those BHs, not only in nearby galaxies but also at cosmological distances, we can hope to unravel the mysteries of galaxy assembly and evolution across cosmic time.

6. Summing Up

Light echoes and reverberation maps are providing exciting new capabilities and discoveries, including the remarkable ability to obtain spectroscopic observations with modern instrumentation of events that occurred decades and even centuries ago. Full exploitation of these techniques requires careful scheduling of synoptic observations and the capability of quick reaction to targets of opportunity.

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