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IOTA: Recent Science and Technology

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ABSTRACT

We present a brief review of recent scientific and technical advances at the Infrared Optical Telescope Array (IOTA). IOTA is a long-baseline interferometer located atop Mount Hopkins, Arizona. Recent work has emphasized the use of the three-telescope interferometer completed in 2002. We report on results obtained on a range of scientific targets, including AGB stars, Herbig AeBe Stars, binary stars, and the recent outburst of the recurrent nova RS Oph. We report the completion of a new spectrometer which allows visibility measurements at several high spectral resolution channels simultaneously. Finally, it is our sad duty to report that IOTA will be closed this year.

Keywords: Infrared, Interferometry, Binary Stars, Mira Stars, Integrated Optics, Closure Phase

1. INTRODUCTION

This paper reviews recent progress in science and technology at the Infrared Optical Telescope Array (IOTA), with emphasis on the work that has been accomplished since the last review.[1]

The IOTA is a long baseline optical interferometer located at the Whipple Observatory on Mount Hopkins Arizona. The interferometer consists of three 45-cm telescopes. The telescopes can be arranged on an L-shaped track. The long arm of the 'L' is 35m in length and oriented roughly NE. The short arm of the 'L' is 15m in length and oriented SE. The maximum baseline obtainable with this configuration is 38m. The overall system layout is illustrated in the photograph shown in Figure 1.

IOTA employs a vacuum delay line system to bring the light from its three telescopes to the beam combining laboratory. A portion of the visible light from each telescope is intercepted to provide input to a high speed camera used as a part of a rapid tip-tilt correction to maintain alignment of the beams. The remainder of the light from each telescope is focussed onto a dedicated, single-mode fiber and then the light from the three fibers is combined in the IONIC 3T integrated optics beam combiner.[2] Fringes are detected using a sensitive HgCdTe (Rockwell PICNIC) detector.[3]

We now turn our attention to a brief review of recent progress and developments at IOTA. IOTA has operated as a two-telescope interferometer from 1995-2003, and beginning in February 2002, it has been capable of three-telescope operation. The system has been used as a test-bed for many ideas in long baseline interferometry.[1]

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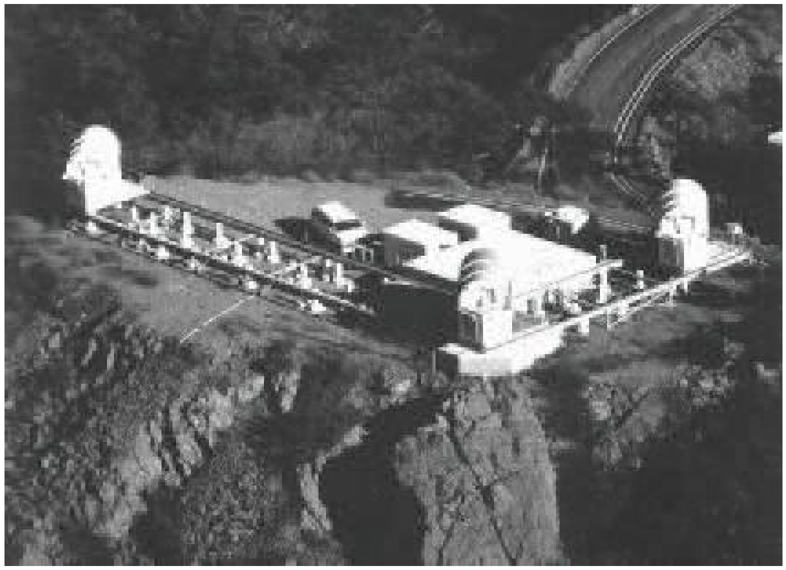

Figure 1. *Infrared Optical Telescope Array, located at Mount Hopkins, Arizona.*

Unfortunately, the most relevant recent news concerning the project is that after 18 years of development and four years as an operational three-telescope system, the IOTA instrument will be decommissioned, beginning on July 1, 2006.

2. RECENT SCIENCE

We now present a short summary of a selection of recent scientific projects which are currently submitted for publication or in press. Many of these results depend directly on the ability of IOTA to measure closure phases with the three telescope system, and therefore, it is useful to review some of the special features of this measurement. The closure phase is defined to be the sum of the three visibility phases measured by a three-telescope system. The closure phase has the useful property that, although the measurement is a linear combination of the visibility phases, the result is not corrupted by the effects of propagation through the atmosphere. Thus, the closure phase is a measurement of a property of the source itself, and for that reason, the measurement has enormous value.

Measurement of a non-zero closure phase indicates that the source is not centro-symmetric (point-symmetric) and detection of a non-zero closure phase is a solid indication that the emission from the source is skewed in some manner. Unresolved sources (sources which are small compared to the spacing of the fringes on the sky) will always have zero phase and hence zero closure phase when all three baselines fail to resolve the source. Thus, the ability of the interferometer to resolve the object is always a key part of the interpretation of a closure phase.

2.1. AGB Asymmetries

A number of physical mechanisms may lead to the formation of features on the surfaces of Asymptotic Giant Branch (AGB) stars. IOTA offers the potential to detect these features through measurement of the closure phase, and a survey of closure phase measurements of 56 nearby AGB stars has recently been completed.[4] The sample includes examples of Mira Variable stars, Semi-regular Variables, and Irregular Variables. These stars were observed with resolutions between 5-10 milliarcseconds in the near-ir H band, and 29% of all stars showed a detectable, non-zero, closure phase. However, when one considers the effects of resolution, it is found that 75% of stars which are well resolved by the interferometer show a non-zero closure phase. This suggests that most AGB stars have features.

2.2. Herbig AeBe Stars

The Herbig AeBe Stars are understood to be pre-main sequence stars of intermediate mass surrounded with preplanetary disks of material that emit in the infrared. IOTA has conducted detailed studies of a number of objects and recently completed a survey of many such stars seeking evidence of asymmetric emission.

2.2.1. AB Aurigae

AB Aurigae is the prototypical Herbig AeBe Star. Long baseline interferometric measurements of AB Aur[5] made with IOTA demonstrated that the circumstellar disk was much larger than expected based on models fit solely to the spectral energy distribution of the Herbig AeBe stars. This result has prompted revision of the models to account for the larger size (see Millan-Gabet et al.[6]) A significant feature of the new generation of models is that the hottest emission from the circumstellar disk arises from thick inner walls of the disk which surround a relatively clear and dust free region around the star. Under these circumstances. one expects to see asymmetric emission from disks which are inclined with respect to the observer. Thus, these are excellent targets for study with a three-telescope system capable of closure phase measurements.

IOTA carried out a major campaign of observations on AB Aur.[7] Figure 2 shows the AB Aur uv-plane coverage obtained in the experiment. Interestingly enough, although the interferometer baselines sampled a wide range of position angle the source showed surprising symmetry in its size over all measured angles, suggesting a nearly face-on geometry for the disk. Measured closure phases on the longer baselines are all close to zero, and consistent with the symmetric emission in sub-AU scales within the source. However, observations on the shortest baselines which probe larger scales, show a small, but detectable, closure phase signal. This is interpreted as an indication of localized, off-center emission at 1-4 AU from the star within the circumstellar disk.

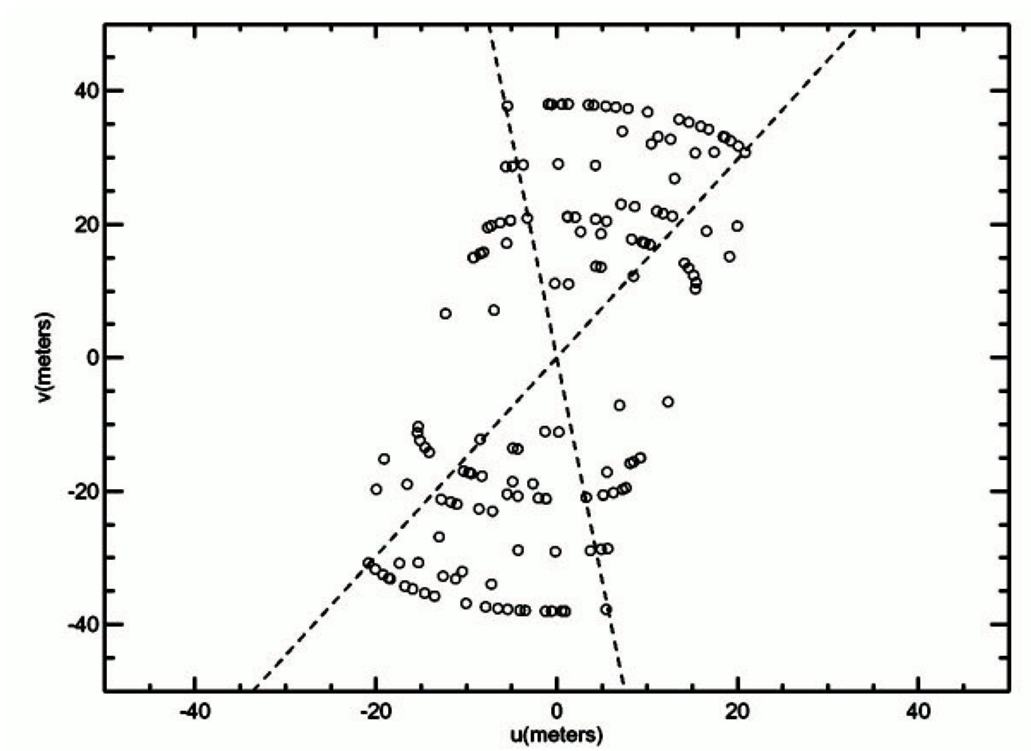

Figure 2. *UV Plane Coverage obtained on AB Aur by the IOTA.*

2.2.2. Herbig AeBe Star Survey

IOTA was used to perform a survey of 14 Herbig AeBe Stars in order to search for evidence of asymmetric emission.[8] As noted above, a non-zero closure phase would generally be expected for observations which resolved a circumstellar disk inclined to the observer. The actual results of the survey are that the measured closure phases tend to be smaller than one might have predicted based on current models. This result is illustrated in Figure 3. For each source, the maximum observed closure phase is plotted against the maxiumum resolution obtained on the source by the interferometer. In general, one expects that as the resolution of the interferometer increases, the degree of asymmetry will become more obvious and the closure phase will increase. This is illustrated through model predictions of a specific disk model due to Dullemond, Dominik, and Natta[9] which shows that the closure phase signature increases as the resolution increases. Interestingly, the actual closure phase measurements obtained show much smaller signatures than would be allowed by this class of model.

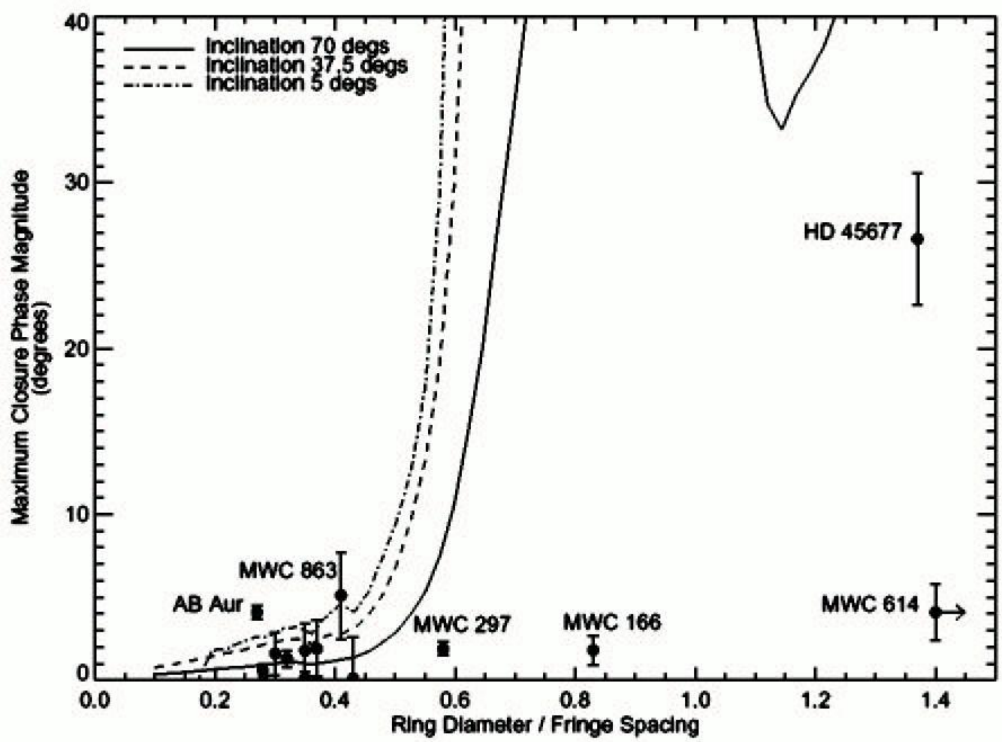

Figure 3. *Summary of results of closure phase survey of 14 Herbig AeBe Stars obtained with IOTA. The graph plots the largest observed closure phase versus the maximum resolution obtained on the source. Model curves, based on the specific model of Dullemond, Dominik, and Natta[9] for three different inclination angles, are shown. Generally, the observed asymmetries are much less that those allowed by this class of model.*

2.3. Binary Stars

Interferometers are well known for their ability to measure the orbits of binary star systems. When the velocities of the stars are measured spectroscopically, the combination of the orbit and the velocity measurements may be used to deduce the masses of the stars directly for comparison to evolutionary models. The binary star λ Virginis is a well known double-lined spectroscopic Am binary, and IOTA measurements have been used with spectroscopic measurements to deduce a physical orbit for the system.[10] The masses and effective temperatures of the components have been deduced and compared to evolutionary models. In Figure 4, the results for each component are compared to evolutionary tracks for a metallicity of Z=0.0097. The comparison shows that the measurements are consistent with a single isochrone (dashed line in figure) for the system, corresponding to an age of 935 MY.

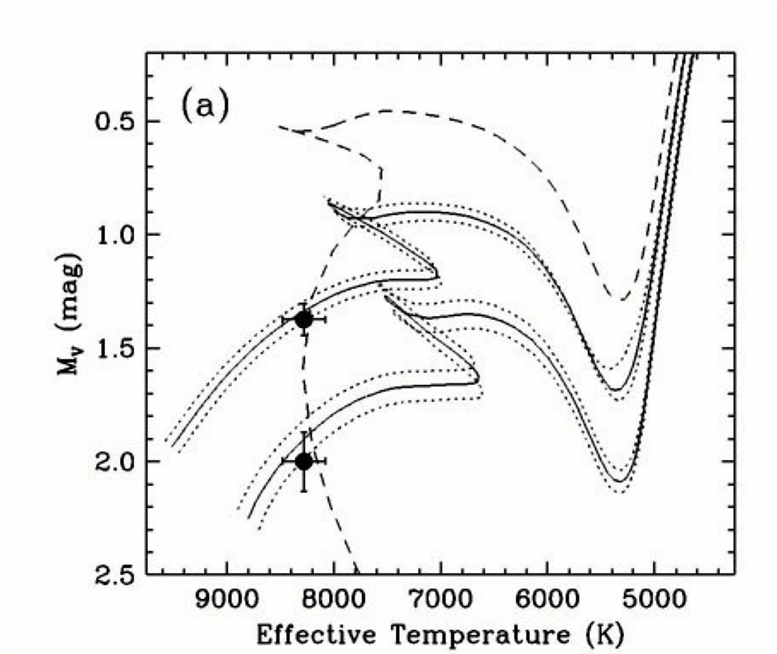

Figure 4. *Comparison of results from λ Vir study to models of stellar evolution. The inferred Luminosity and Effective Temperatures of the components of this binary system are consistent with calculations of their evolutionary tracks assuming the measured masses and a single system age.*

2.4. RS Ophiuchi

RS Oph is one of a few known 'recurrent novae' which have been observed to produce outbursts multiple times in recorded history. The most recent outburst occurred on February 12, 2006, and it was sufficiently bright to be observed at IOTA and at other interferometers. The recurrent novae are likely to arise from a phenomenon similar to the "Classical Novae", wherein material being accreted onto a white dwarf in an interacting binary system becomes massive enough to initiate hydrogen burning. The sudden explosion caused by the ignition of H-burning produces an expanding fireball of emission from the nova. Therefore, in observations which resolve a nova, one might expect to see evidence of the expansion of the fireball over time.

Surprisingly, although observations of RS Oph with IOTA were able to resolve the source of the emission, no evidence was found for a change in the size of the source with time.[11] Figure 5 shows the IOTA visibility measurements (points shortward of 25 mega-wavelengths) at three different epochs following the outburst. Formal fits to visibility data show no detectable change in size. In addition, measurements of closure phase show small, non-zero, values indicative of asymmetric emission. This may be consistent with direct detection of the underlying binary, although other interpretations of this asymmetric signature are also possible.

3. RECENT TECHNOLOGY

Measurements of the size of Mira Variable Stars at high spectral resolution in the near-ir have shown interesting variations which are through to be due to the presence of water in the envelopes of the stars.[12] For this reason, the IOTA group sought to build a special purpose spectrometer which would allow simultaneous measurments of visiblity in several high spectral resolution channels. The new instrument is a prism spectrograph which disperses the combined beams from the interferometer and allows the visibility to be measured in seven narrow channels (or three somewhat broader channels) across the H band. The new instrument was completed and tested during the spring of 2006. Figure 6 shows the first light fringes obtained in seven spectral channels for the three-baseline IOTA system. We now hope to use the new system at other interferometric instruments after IOTA is closed.

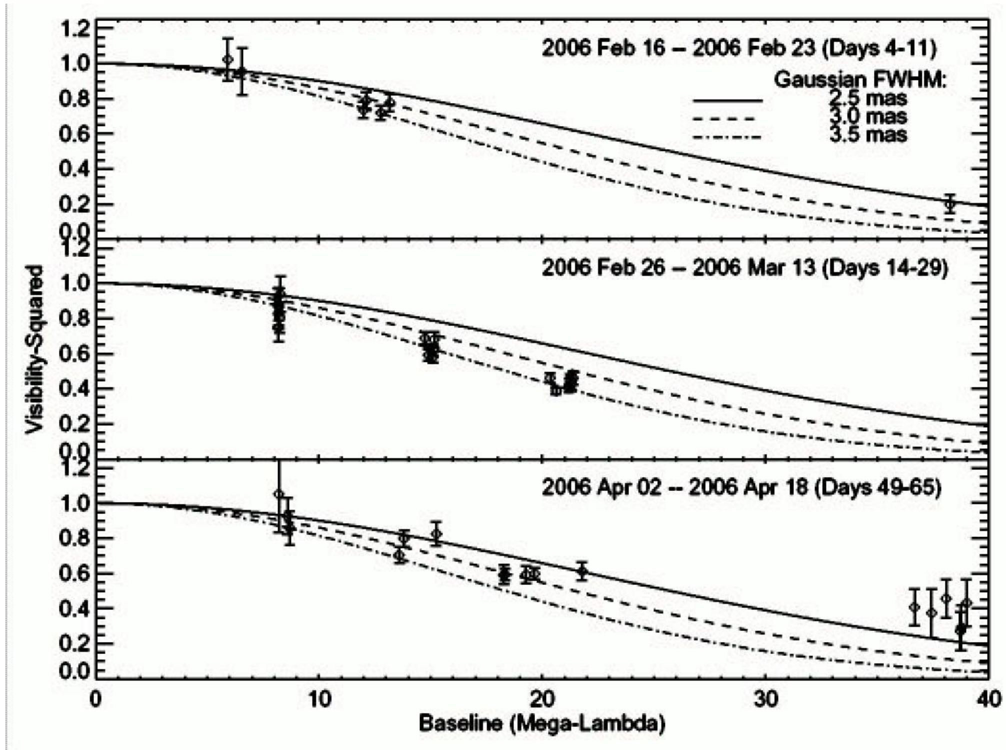

Figure 5. *Measurements of the visibility of RS Oph at three epochs following the outburst of February 12, 2006. All data obtained for baselines less than 25 Mega-wavelengths were obtained with IOTA. The long baseline data for the first epoch were obtained at the Keck Interferometer. The long baseline data obtained for the third epoch were obtained at the Palomar Testbed Interferometer. Formal fits to the IOTA data show no detectable change in the size of the emission region during this time.*

4. EPILOG

The IOTA collaboration is proud of our record of accomplishment and our contributions to the field of long baseline optical interferometry. IOTA began with an agreement in 1988 among five Institutions, the Smithsonian Astrophysical Observatory, Harvard University, the University of Massachusetts, the University of Wyoming, and MIT/Lincoln Laboratory, to build a two-telescope stellar interferometer for the purpose of making fundamental astrophysical observations, and also as a prototype instrument on which we could perfect techniques which could later lead to the development of a larger, more powerful array. First fringes with the two telescope system were obtained in December 1993.

In the past recent years the membership has evolved as the location of participant scientists have changed, so that currently SAO, Harvard, and UMass are active from the original five, and six new institutional affiliation have begun: Instituto Nacional de Astrofisica, Optica y Electronica (INAOE), Observatoire de Grenoble, Observatoire de Paris- Meudon, NASA Ames Research Center, ESO (Garching) and MPIA (Heidelberg), the last two participating via individual scientists. IOTA carried out a major upgrade to 3 telescopes with the support of NASA and the NSF and achieved three telescope operation in 2002.

During our eighteen years of collaborative work, we have produced over 100 scientific and technical papers, and more importantly, we have contributed to the growth of our field with 20 student thesis projects. Thanks to those students, and to the hard work of all of our colleagues, we are confident that IOTA will have the sort of lasting impression on the development of optical interferometry that was envisioned when we began this project.

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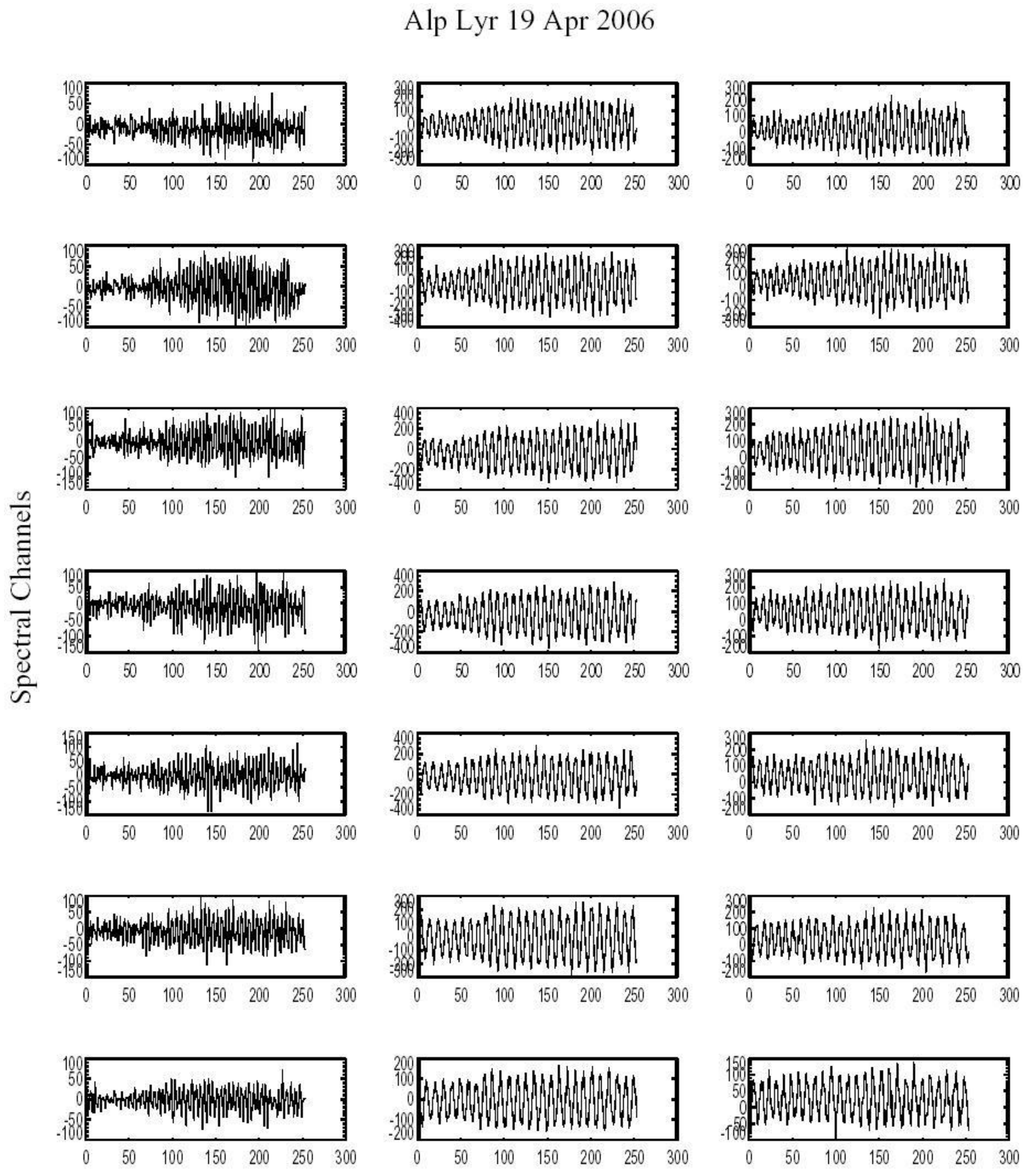

Figure 6. *First Light fringes measured with high resolution spectromenter on IOTA. The figure shows the fringe packet for each wavelength (rows) and for each baseline (columns) in the system.*