The Magdalena Ridge Observatory Interferometer: Progress Towards First Light and Science

211th American Astronomical Society Meeting - Wednesday, January 9, 2008

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Introduction:

The Magdalena Ridge Observatory Interferometer will be a 10-element optical and near-infrared model-independent imaging interferometer, due for first light in 2009. It is located in the Magdalena Mountains, about 45 minutes west of Socorro, NM at 10,500 feet. The interferometer is being designed by a collaboration between New Mexico Institute of Mining and Technology and the University of Cambridge. The science reference mission for the interferometer, from which we derive the design requirements, has three main components: i) the study of stellar and planetary formation, ii) developing a better understanding of physical processes at various stages of stellar evolution, and iii) characterization of the innermost regions of active galactic nuclei. Below is a brief discussion of each of these key areas, the subsequent design requirements they place on the interferometer, and the current status of the interferometer design and timelines to first light.

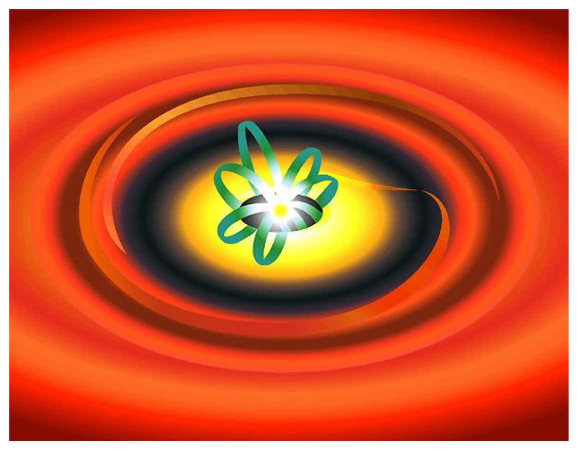
Key Science Mission:

Interferometry offers the only route to reach the angular resolutions required to provide direct and detailed observational constraints on many fundamental astrophysical phenomena. In simple cases, where the physics and a priori models are thought to be well-understood, a single measurement or single-baseline may suffice (e.g. measuring the angular diameter of a singular star or characterizing the orbit in a non-interacting binary system). However, for most interesting astrophysical problems, our a-priori picture is at best rudimentary, because even the basic geometry is frequently in doubt. These simple facts highlight the need for an *imaging* interferometer which can produce model-independent images of complex astrophysical systems by imaging with the appropriate angular and spectral resolutions. We have identified the following science as our key science mission upon which the design requirements for MROI are based and are beginning the formation of science working groups this spring in 2008.

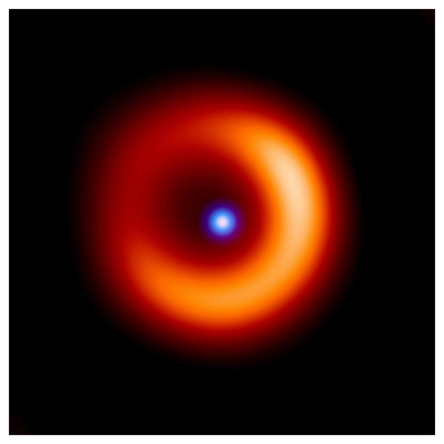
Part I -- Stellar and planetary formation:

The birth of stars is of central importance to astrophysics, while the formation of planets is of fundamental interest to all of mankind. These two phenomena are inextricably linked because planets form from the leftover material of the star formation process. After the collapse of an interstellar gas and dust cloud, a flattened, rotating disk of infalling material emerges. The physical mechanisms controlling the accretion onto the new star in this disk lie at the heart of the star formation process. At some time during this process, planets are known to form, though the details are still under debate.

Some of the fundamental questions that arise from the studies of star and planet formation processes are: i) Is the disk clearing period contemporaneous with the epoch of planet formation? ii) What can astronomers learn about jets, outflows and magnetically channeled accretion? iii) What evidence is there regarding the sub-AU geometry of disks and gaps through imaging of the thermal dust? iv) What is the frequency of occurrence of sub-stellar mass companions? v) What is the chemical composition and physical characteristics of these companions through direct spectral imaging?



Artist's conception of magnetically channeled accretion and disk clearing in a protostellar accretion disk.

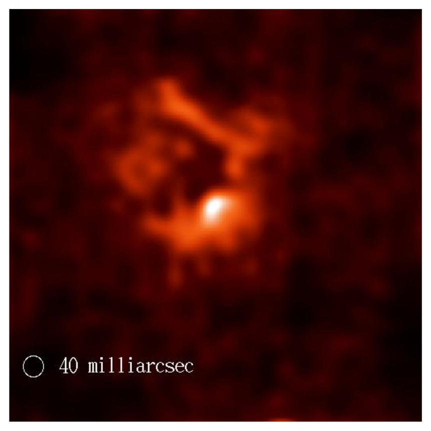


Keck aperture masking image in the near-infrared of LkHa 101, constrained by NIR IOTA data. Tuthill et al., 2002, ApJ, 577, 826.

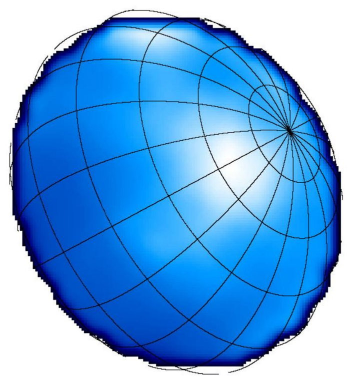
In order to answer these and other questions, MROI needs to have the sensitivity to image the thermal dust emission from disks out to a diameter of ~0.2 AU in the nearest (<500 pc) star forming regions. It needs sufficient spectral resolution to image the locations of emission lines from magnetically channeled accretion at 5-10 stellar radii (Hartmann et al. 1994). The array needs to have snapshot imaging capability at H-alpha to study the rotation rates in the accretion disks in order to obtain a direct measure of the shearing forces. And finally MROI needs to be able to discriminate 0.1 AU clearings in the disks caused by planetary formation.

Part II -- Stellar Evolution:

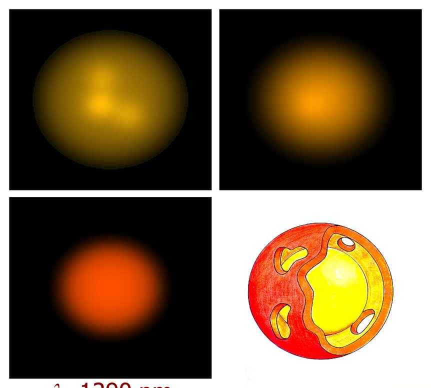
For the majority of their lives most stars fuse H quiescently. After this fuel is exhausted, nuclear burning progresses through He core burning, while H and He shell burning commence. Hydrodynamical instabilities set in, ongoing convection destabilizes the star, and a phase of catastrophic mass-loss ensues in which as much as 80% of the total stellar mass may be lost. The onset and progression of this process is still one of the most poorly understood areas in stellar astrophysics. The picture becomes more complicated if the evolution occurs in a binary system in which mass transfer, circumbinary disks and run-away surface burning may occur in conjunction with the mass-loss stage.



Keck aperture masking image in the near-infrared of evolved carbon star IRC+10216. The complex distribution of K-band flux is indicative of highly clumpy, anisotropic mass loss that is not apparent in indirect measures of the source, such as SED fits. Monnier et al., 2000, ApJ, 543, 861.



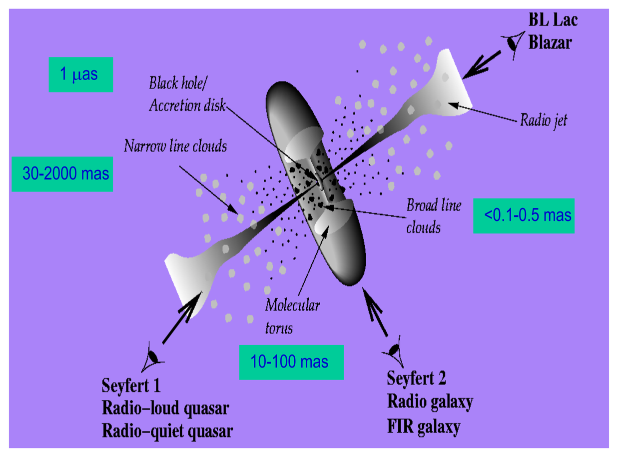
CHARA image of rapidly rotating star Altair using the new four-way infrared beam combiner MIRC. The effects of the von Zeipel effect are evident by the distribution of hot and cool zones. Monnier et al., 2007, Science, 317, 342.



COAST optical and near-infrared images of supergiant Alpha Ori and based on data from Young et al. 2000, MNRAS, 315, 635.

Dozens of fundamental physical questions arise from detailed studies of these processes including: i) How can one best describe the convection processes – are they latitudinal, longitudinal? ii) How many convection cells dominate a stellar surface? iii) Is the mass-loss process generally bipolar and at what phase does this bipolarity set it? iv) What part do acoustical shocks and Alfven waves play in mass-loss? v) What are the intricate wind, orbit and accretion geometries in interacting binary systems? vi) Is the mass transfer clumpy or smooth in eclipsing binary systems? vii) What are the correct descriptions of the pulsation modes (fundamental, overtone, non-radial, etc.) in various intrinsic variables (e.g. Cepheids, RR Lyrae, miras)?

In order to begin to understand these physical processes, MROI will have the angular resolution to image scales from stellar pulsation at the order of 10% of a stellar radius, up to mass loss outflows at hundreds of AU. It needs high dynamic range to image the potential clumpy nature of mass-loss and to resolve spots on stellar disks. And it needs moderate spectral resolutions to observe lines in, e.g. TiO, CO, H_2 and H-alpha to study ionized regions, shock fronts, and particular stellar lines of interest.



Artist's conception of a unification theory for the appearance of various AGN. Superimposed are typical angular scales for various regions of the AGN. This picture was taken from the cover of Krolik's book on AGN.

Part III -- Active galactic nuclei (AGN):

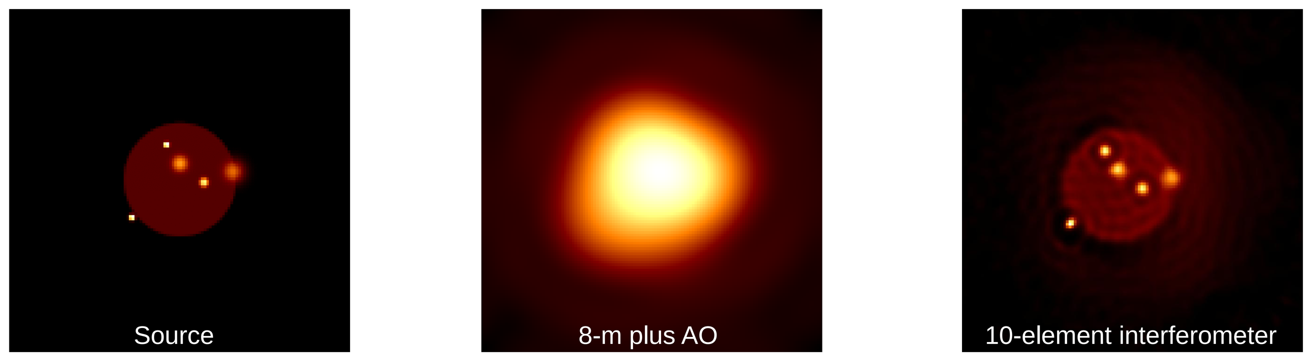
The cores of AGN, where gas and dust are believed to be spiraling in towards a massive black-hole, are some of the most energetic and enigmatic objects in the Universe. Much current knowledge of these systems comes through indirect methods e.g. spatially unresolved spectroscopy and variability studies of broad emission lines regions and techniques like reverberation mapping. Their large distances mean that few except the brightest at radio wavelengths have had their cores imaged with any appreciable spatial resolution. An optical interferometer, designed to image the broad and inner narrow-line emitting regions at the hearts of these AGN, will allow astronomers to make tremendous inroads in our knowledge of these sources.

Many of the most fundamental questions about AGN physics will be centered around the verification of unification theories and involve the direct detection, measurement and characterization of the purported obscuring tori at the centers of AGN. In particular, astronomers want to know how the torus' properties are related to the larger scale galactic structure. Other key programs will investigate the nature and contribution of the nuclear and extra-nuclear starbursts, the dynamics of the broad-line region, and the presence and properties of the optical/IR counterparts of synchrotron jets.

To answer these fundamental questions the array needs a sensitivity of 14th magnitude at H-band for group delay tracking in order to have access to a statistically significant sample (>100) of objects. It also needs angular and spectral resolutions significant enough to image, in particular, the broad-line clouds and molecular torus of the AGN.

The Power of Imaging with an Interferometer:

The true power of imaging with an optical interferometer can be seen when comparing a simulated image of a star with spots and flux reconnection loops (*left image below*) to images taken by either an 8-m class telescope with Adaptive Optics running with *100% Strehl* (*central image*) or the 10-element MROI baselines with 1% visibility errors (*right image*). The simulated star in this image is approximately 20 milliarcseconds in diameter and data processing was done using BSMEM.



Flow-down from Science to Design of the MRO Interferometer:

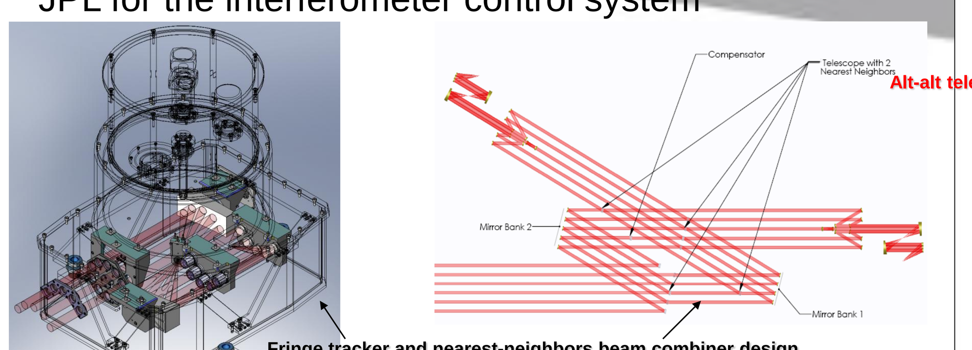
To usefully address these key science areas, any interferometer will need at least the following characteristics – all of which will be featured in the MROI:

- Operation in the optical and near-infrared so as to access key diagnostic emission lines and hot dust.
- The ability to optimize the array to deliver images of variable angular resolution (like the re-configurable VLA) from 0.1-100 mas.
- A sensitivity that allows stabilized fringe sensing for targets with cores as faint as 14th mag at H (1.6 microns) – this requires telescopes at least 1.4m in diameter with low-order AO and is crucial for challenging studies of AGN and star-forming regions.
- The ability to image efficiently in "snapshot" mode which demands at least 6 and eventually 10 array elements in the interferometer.

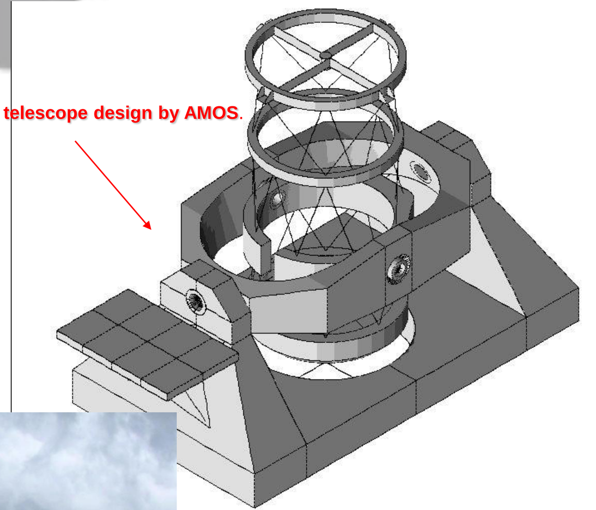
Design Progress and Status

The design of all major subsystems of the MROI is nearing completion; most have passed their conceptual design reviews (coDRs) and many are now in the build phase. Significant near-term progress includes:

- Long-stroke vacuum delay line trolleys being prototyped and built by University of Cambridge (FDR in Feb 2008)
- Beam combining and control buildings (designed by *M3 Engineering and Technology Corp* -- occupancy certificate received in Dec 2007)
- The design and build contract for the unit telescopes with *AMOS* (responsible for the 1.8m VLTI telescopes – CDR in March 2008)
- Six sets of 1.4m optics are currently being figured and polished by *OST* in Albuquerque
- Ongoing procurement and assembly of the fringe tracking nearest-neighbors (pupil plane) style of beam combiner and cryogenic IR camera
- Adoption of linux-based RTC (*Real-Time Control*) as software infrastructure from JPL for the interferometer control system

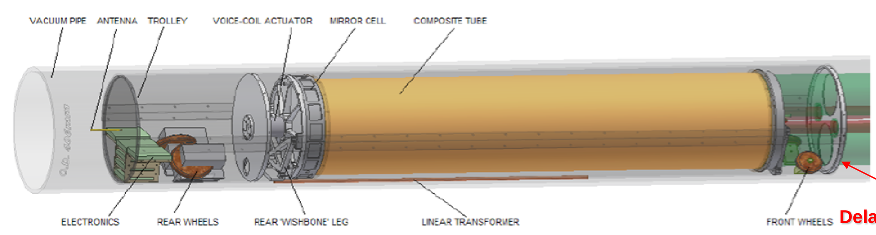


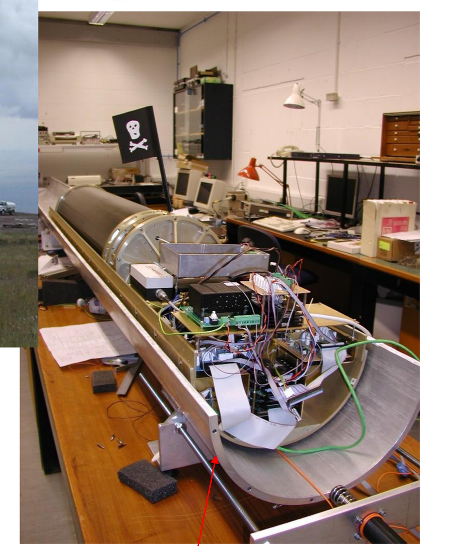
Fringe tracker and nearest-neighbors beam combiner design.



Alt-alt telescope design by AMOS.

Beam combining and delay line buildings on the Ridge in Sept. 2007





Delay line trolley design and actual cart in April 2007

We expect first light and first fringes in late 2009, with first closure phase measurements in 2010. Phase A deployment (6 telescopes and the IR science capability) is to be completed in late 2011. Phase B (10 telescopes and optical science) will begin when more funding for unit telescopes, associated delay lines and an optical beam combiner is acquired.

Thirteen detailed Performance Verification Milestones (PVMs) have been identified to reach full technical operability of the Phase A deployment of the array. Coupled with these are the science timeline: first fringes and "first light" science correspond to PVM5 (2009-10). Deep sensitivity measurements take place after PVM7. Closure phase based science begins at PVM9 (2010-11), and snapshot capabilities will be fully employed during PVMs 10-13 (2011-2012). Science Verification Milestones (SVMs) are being developed and detailed lists of science targets and preparatory work will begin this Spring in the Science Working Groups (SWGs) for MROI. It is expected that any MROI partner institutions and members of the science working groups will participate in shared-risk science observations during the later PVMs listed above. Contact M. Creech-Eakman, Project Scientist, for more information about MROI key science or SWGs.

We expect to advertise more job openings in 2008 (check the AAS Job Register) for positions on our team. For more information about MROI – please visit our website: http://www.mro.nmt.edu or visit us at the NMT campus Research Park.

We would like to thank our sponsors at NRL and in Congress for the funding for the Magdalena Ridge Observatory and SFTC for support of our UK-based colleagues.