Magdalena Ridge Observatory Interferometer Science Mission and Design Requirements

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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 2008. 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 discussion of each of these key areas, the subsequent design requirements they place on the interferometer, and the current status of the interferometer contracts.

Reference Science Mission:

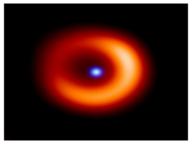
Interferometry offers the only route to reach the angular resolutions required to provide direct and detailed observational constraints on many fundamental astrophysical phenomena. In simple cases, where the physics and a priori models are thought to be well-understood, a single measurement or single-baseline 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.

A very wide range of scientific projects is possible with an imaging interferometer that has angular resolutions in the sub-milliarcsecond regime, and operates at visible and near-infrared wavelengths. We have identified the following science as our key reference science mission upon which the design requirements of the MROI are based.

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.

Artist's conception of magnetically channeled accretion and disk clearing due to a planet in a protostellar accretion disk. The MROI will be the first instrument to be able to resolve the central hole and the accretion arcs, as well as detect planets via gaps and spiral streams.



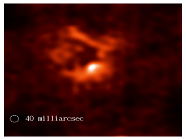
Keck aperture masking image in the near-infrared of young stellar object LkHa 101. In this interferometric image, the dust clearing in the inner region of the disk is clearly evident. Tuthill et al. (2001)

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 ongoing physics is evident in the sub-AU disturbances of disks? iv) What is the frequency of occurrence of sub-stellar mass companions? v) What is the chemical composition and physical characteristics of these companions, as evidenced through resolved spectral imaging?

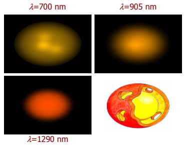
In order to answer these questions and others, the MROI will have the sensitivity to image the thermal dust emission from disks out to a diameter of ~0.2 AU in the nearest (<500 pc) star forming regions. It will have sufficient spectral resolution to image the locations of emission lines from magnetically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

Stellar Evolution:

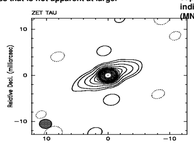
For the majority of their lives most stars (like the Sun) fuse hydrogen rather quiescently. After this fuel is exhausted, nuclear burning progresses through helium core burning, while various types of shell burning commence. Hydrodynamical instabilities set in, ongoing convection destabilizes, and a phase of catastrophic mass-loss ensues in which as much as 80% of the total mass of the star may be lost. The onset and progression of this process is still one of the most poorly understood areas in stellar astrophysics. This picture becomes considerably 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 at larger angular scales. Tuthill et al. (2000).



COAST optical and near-infrared images of supergiant Alpha Ori, where there is a clear indication of stellar spots. Young et al. 2000 (MNRAS 315, 635).



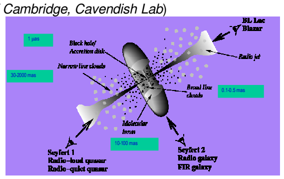
COAST H-alpha image of the Be star and disk – Zeta Tau (George, PhD Thesis, Univ. of Cambridge, in prep). Evidence for the disk structure is clear.

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 in? iv) What part do acoustical and other shocks 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, Miras, RV Tauris)?

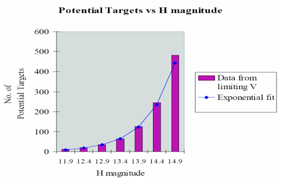
In order to begin to understand these physical processes, MROI will have the angular resolution to image scales from 10% of a stellar radius in order to measure stellar pulsation, up to hundreds of AU for characterizing mass outflows. It will have high dynamic range to image the potential clumpy nature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

Active galactic nuclei (AGN):

The cores of active galactic nuclei, 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. Despite their importance, much current knowledge of these systems comes through indirect methods e.g. spatially unresolved spectroscopy and variability studies of their broad emission lines. Their large distances mean that few except the brightest have had their cores imaged with any appreciable spatial resolution, and then only in the radio. 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.



Artist's conception of a unification theory for the appearance of various active galaxies and quasars. Superimposed are typical angular scales for various regions of the AGN. This picture was taken from the cover of Active Galactic Nuclei, J. Krolik, 1998, Princeton Press.



The potential number of AGN and quasars (in the N hemisphere) as a function of H-band core magnitude based on the catalogue of Veron-Cetty and Veron (A&A 374, 92).

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 (e.g. the orientation of the rotation axis). 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 MROI will have a sensitivity of 14^{th} magnitude at H-band for group delay tracking in order to have access to a statistically significant sample (>100) of objects (*see plot above*). It will also have angular and spectral resolutions sufficient to image, in particular, the broad-line clouds and molecular torus of the AGN.

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

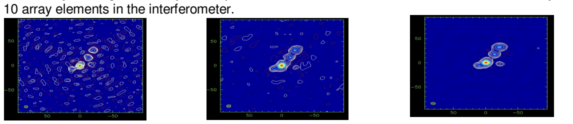
To usefully address these key science areas, any interferometer will need at least the following characteristics – all of which will be featured in the MROI:

• 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 milliarcseconds.

•A sensitivity that allows fringe sensing for targets with cores as faint as 14^{th} magnitude at H – this requires telescopes at least 1.4m in diameter and is crucial for challenging studies of AGN and star formation regions.

•The ability to image efficiently in "snapshot" mode. This will demand at least 6 and eventually 10 array elements in the interferometer.



Results of simulations of 4, 6 and 8 element arrays. Contour levels are at ½, 1, 2, 4, 8, 16, 32 and 64% of the peak emission. The beam is shown in the lower left hand corner of each image. The 8-element array builds up a much cleaner image of the source 7 times as quickly as the 4 element array.

Status

The design of a large fraction of MROI has been completed. The delay line, beam combining and control buildings are being designed by *M3 Engineering and Technology Corp.*, and we expect construction of these to commence in Spring 2006, and to be completed in Summer of 2007. We are in the process of finalizing the unit telescope, dome and telescope transporter procurement, and are close to completing negotiations with JPL on the use of their RTC (*Real-Time Control*) software for the interferometer control infrastructure under Linux. The University of Cambridge is currently prototyping the long-stroke vacuum delay line carriages for the array. We are mid-way through a phase-A study of beam combiner concepts and are looking at downselecting in April of 2006. We expect first light and first closure phase measurements to be realized in 2008, and that Phase A deployment (6 telescopes and the IR science capability) to be completed in late 2009. Phase B (10 telescopes and optical science) will begin as and when more funding for unit telescopes and an optical beam combiner is acquired.

For more information about MROI – come see our booth here at the AAS or visit our website: *http://www.mro.nmt.edu.*

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