FOE: Faint Object Explorer
Astrophysics

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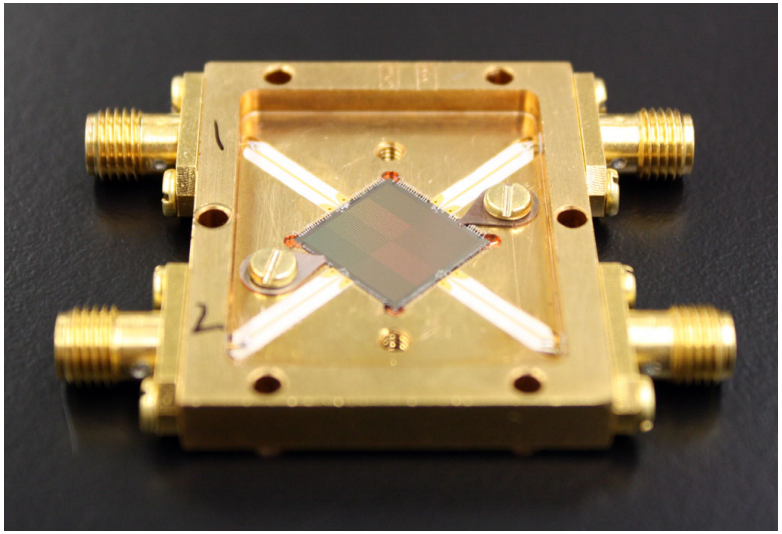
Equip the NRO telescope with a Megapixel energy-resolving MKID array. Place it in a 2 AU inclined orbit to allow R=50, 0.2-1.8 μm imaging spectroscopy on 30th magnitude objects in 20 ksec.

Observing Speed 500x HST!



Description:

Combine two powerful new technologies, MKID focal planes and Solar Electric Propulsion, with the NRO telescope to build an instrument with 500x the observing speed of HST.

FOE, the Faint Object Explorer, will be a general purpose, narrow field of view, UVOIR observatory of unprecedented sensitivity.

MKIDs have taken science data at ground-based telescopes, TRL 4-5.
The SEP technology needed to reach this orbit were assessed as TRL 5-6 during a SMD review during FY12

Our team is made up of researchers from UCSB, Goddard, and JPL. A natural division of labor would have Goddard working on the SEP system, and JPL and UCSB continuing their development of MKIDs.

Value to NASA:

FOE would provide astronomers with a uniquely powerful observatory, even in the era of 30-m class ground-based telescopes.

FOE directly addresses nearly every science theme called out in the recent Astro2010 New World, New Horizons report, from studying Cosmic Dawn (observing the first galaxies and black holes), to Physics of the Cosmos (measuring cosmological parameters, detecting the stochastic gravity wave background through pulsar timing), and New Worlds (transit spectroscopy). FOE would also be a powerful tool for studying solar system objects like KBOs.

SALSO: Faint Object Explorer (FOE)

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1 Introduction

Forecasting the scientific landscape more than a decade from now is difficult, but one thing will always be true — the faintest objects are always going to be among the highest priority targets, since that is where our knowledge reaches its limits. We propose using the second NRO telescope for a UVOIR mission we call FOE, the Faint Object Explorer. FOE will use a combination of two novel techniques to allow unprecedented sensitivity, significantly exceeding HST and JWST in its point source sensitivity. First, FOE will use the 2 AU inclined orbit developed by Greenhouse *et al.* at Goddard for astrophysics Explorer missions, providing the darkest sky ever for an astrophysics mission — a factor of 100x darker than Hubble's orbit! This will be especially powerful for extended sources. Second, FOE will feature an energy-resolving, Megapixel focal plane composed of MKID detectors. These photon counting detectors, similar to X-ray microcalorimeters, feature sensitivity from 1000 to 18000 Å (far UV to H band), intrinsic energy resolution R=E/ΔE=50 at 2500 Å, microsecond timing accuracy, no read noise or dark current, and nearly perfect cosmic ray rejection. Compared to HST, FOE improves the observing speed by a factor of 10 from the orbit, and 50 by doing simultaneous medium band photometry, giving a total ***observing speed increase of 500***×! In 20 ksec, FOE would obtain a broadband, low resolution image cube on a m_V=30 point source with a SNR of >10 in each of its ∼50 wavelength bins.

2 Science Goals

FOE will be a general purpose facility for deep, broad band, low spectral resolution integral field spectroscopy, as well as an instrument of unprecedented power for time-domain astronomy. It will be useful for nearly every science priority laid out by the Astro2012 New Worlds, New Horizons (NWNH) report. An incomplete list of science goals includes:

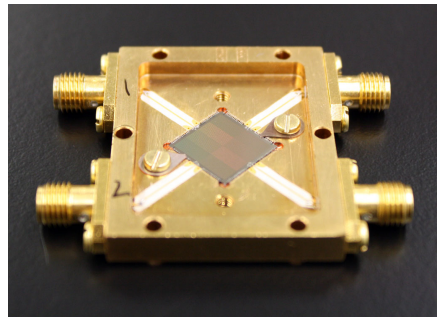

Figure 1: A photograph of the ARCONS 2024 pixel MKID array (with microlens removed for clarity) in a microwave package.

Deep, time resolved, UV through near-IR Followup of JWST/WFIRST/EUCLID /LSST targets. UV through optical follow up of future surveys will be extremely difficult, as there will be no HST and the AO systems required for 30-m class telescopes will limit them to wavelengths longer than 1 μm. FOE will enable high spatial resolution UV through H-band imaging spectroscopy. FOE will be a powerful complement to JWST and future surveys, addressing a gaping hole in our future space UV and optical capabilities. Directly addresses the "Cosmic Dawn" science themes of NWNH.

Measurement of the Stochastic Gravity Wave Background. FOE pays no signal to noise penalty for observations of rapidly rotating sources, and the combination of the 2.4-m aperture and the essentially negligible sky background and wide passband will allow the timing of millisecond pulsars with 1 microsecond accuracy down to an $m_V \approx 29$. This will allow new era of millisecond pulsar timing for gravitational wave detection. The optical/near-IR does not suffer from dispersion or scintillation which may well be the dominant sources of timing error in gravitational wave detection with pulsars at radio wavelengths [1]. Directly addresses the "Physics of the Universe" science themes of NWNH.

Strong Lensing. The high spatial and energy resolution will allow an unprecedented reconstruction of both galaxy and cluster-scale strong lenses. High spatial resolution imaging spectroscopy of quad lenses, combined with

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ground (LSST) or space-based time series photometry can provide measurements of cosmological parameters with extremely high precision [2]. Directly addresses the "Physics of the Universe" science themes of NWNH.

Transit Spectroscopy. Many of the transiting planets discovered with Kepler are too faint for conventional transit spectroscopy. FOE will provide a means to do transit spectroscopy on systems with faint primaries, as well as observing transits of solar system objects like KBOs. Directly addresses the "New Worlds" science themes of NWNH.

Compact Objects. The nearly background free photon counting and millisecond time-tagging of FOE will provide RXTE-like capabilities in the UVOIR. This unique capability could lead to significant advances in understanding compact objects. Addresses the "Physics of the Universe" science themes of NWNH.

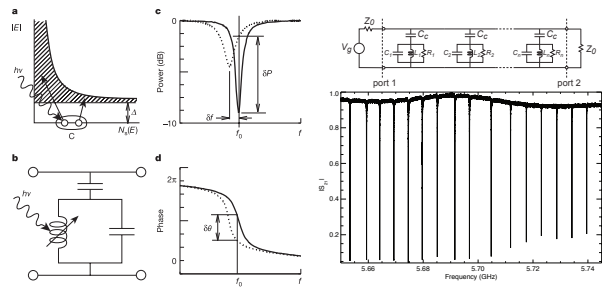

Figure 2: Left: The basic operation of an MKID, from [3]. (a) Photons with energy $h\nu$ are absorbed in a superconducting film, producing a number of excitations, called quasiparticles. (b) To sensitively measure these quasiparticles, the film is placed in a high frequency planar resonant circuit. The amplitude (c) and phase (d) of a microwave excitation signal sent through the resonator. The change in the surface impedance of the film following a photon absorption event pushes the resonance to lower frequency and changes its amplitude. If the detector (resonator) is excited with a constant on-resonance microwave signal, the energy of the absorbed photon can be determined by measuring the degree of phase and amplitude shift. Right: An example of frequency domain multiplexing (FDM) of MKIDs showing how many resonators can be read out through a single transmission line.

3 Technology

Semiconductor detectors are the most common type used in the optical and near-IR wavelength regime because they feature large formats, high quantum efficiency, and low readout noise. However, they are fundamentally limited by the semiconductor band gap and thermal noise from their high (≈ 100 K) operating temperatures. Cryogenic detectors, operating at $\approx$100 mK, allow the use of superconductors with gap parameters over a thousand times lower. A superconducting detector can count single photons with no false counts while determining the energy (to a few percent) and arrival time (to $\approx 1\mu$s) of the incoming photon. Since the photon energy is always much greater than the gap energy, much broader wavelength coverage is possible, enabling observations at infrared wavelengths that are vital to understanding the high redshift universe.

MKIDs [3] are the most successful UVOIR cryogenic detector technology. Their operational principle is shown in Figure 2. Intrinsic frequency domain multiplexing allows thousands of pixels to be read out over a single microwave cable [4]. They can count individual photons with no false counts and determine the energy and arrival time of every photon with good quantum efficiency [5]. Their physical pixel size and maximum count rate are well matched with the NRO telescopes. The MKIDs described here are sensitive to 0.1 - 2 μm wavelength radiation (with cutoffs imposed by the thermal emission from mirrors and the properties of the materials being used) but are optimized for UVOIR wavelengths (200 - 1800 nm). Previous problems with substrate events degrading the energy resolution have been completely eliminated by going to thicker TiN films.

The first optical/nIR MKID camera, the ARray Camera for Optical to Near-IR Spectrophotometry (ARCONS), was commissioned in July, 2011 at the Palomar 200 inch telescope over 4 days [6]. An image of the MKID array used in ARCONS is shown in Figure 1. ARCONS has recently been upgraded to 2024 pixels and now has a total of 24 observing nights on 5-m class telescopes. We have observed a broad range of science target with it, including interacting binaries (AM Cvns, LMXBs, short period eclipsing sources), QSOs (for low resolution redshift measurements), supernovae (Type Ia and Type II), and the Crab, PSR B0656, and Geminga pulsars. Several science papers are currently being written. MKIDs are at least at TRL 4-5.

MKID pixel counts are bottlenecked by the speed and dynamic range of ADCs and FPGAs, which are improving with Moore's Law. 25 kpix arrays are feasible now, and we expect Megapixel arrays by the end of this decade. A Megapixel array Nyquist sampling the diffraction limit at 4000 Å yields a field of view of 21×21 arcseconds. MKID plate scale is adjustable within an array, so a Nyquist sampled core and larger outer array is feasible. Most of the science goals of FOE could be done with smaller MKID arrays.

The radiation environment outside LEO can be challenging, as demonstrated by Planck. MKIDs should perform extremely well here, as the fast time constant of the detectors ($\sim$100μs) will limit the duration of the disturbances due to cosmic rays. Our current readout already takes out slow drifts (>100 ms) such as those caused by the 100 mK stage temperature fluctuating. The lack of semiconductors and the durable nature of the MKID materials (TiN) should limit long term degradation, but more study is needed.

It is reasonable to expect that the energy resolution, R=E/ΔE, of the devices, currently $\approx$20 at 254 nm ($\approx$12 at 423 nm), will continue to improve towards the theoretical limit of 150 at 254 nm over the next several years as designs and materials evolve. Furthermore, the parallel technologies of infrared-blocking filters, broadband antireflection coatings, and detector quantum efficiency continue to develop, which will increase the performance of FOE.

The 2 AU inclined orbit, and the solar electric propulsion (SEP) technology to achieve it, has been studied for a variety of planetary and astrophysics missions, most recently in context of infusion into the Astrophysics Explorer Program. This work should be directly applicable to the NRO telescope. Figure 3 shows the increase in observatory performance as a function of wavelength for this orbit compared to a standard LEO or L2 orbit. Development of the SEP system for FOE is directly responsive to the technology recommendation of the Planetary Decadal Survey, is enabling to Astrophysics Decadal Survey missions such as the New Worlds Explorer, and is responsive to the Office of the Chief Technologist (OCT) road map for in-space propulsion to enable human exploration objectives. For details on this orbit and the potential for astrophysics missions, see Greenhouse *et al.* [7]. The SEP technology needed to reach this orbit were assessed as TRL 5-6 during a SMD review of its NASA Evolutionary Xenon Thruster program during FY12.

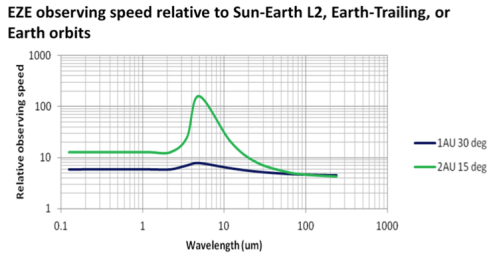

Figure 3: The observing speed as a function of wavelength for different orbits.

4 Conclusion

FOE is a tremendously powerful instrument using innovative technologies like MKIDs and SEP to dramatically increase its utility over the similarly sized HST. FOE fits into NASA's plans beautifully — wide field capabilities will be covered with WFIRST, and deep IR with JWST, leaving an obvious niche for a UVOIR instrument optimized to obtain the most possible information on rare faint objects. While the R=50 low resolution spectroscopy may sound limiting, at the magnitudes (>27) that FOE will be working there are simply not enough photons for higher resolution work. All the technologies for FOE are already at least at TRL-4, and the straightforward design with a single instrument should allow for a reasonable cost.

References

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