Chapter 9 of "A Proposal to NOAO for the Dark Energy Survey", July 15 2004

9. Community Science with the DECam and the DES Legacy Archive

The Mosaic Cameras installed at the NOAO 4m telescopes, north and south, are the most popular facility instruments at NOAO. Over the last two years, the CTIO 4m imager has been assigned 42% of the total nights available. The present Mosaic imagers cover a 0.36 sq-degree field at prime focus in an 8Kx8K format, with a 100s read time. These optical imagers are the largest field imagers routinely available to US astronomers, and they support a wide range of highly-ranked science, such as planet searches, trans-Neptunian object surveys, maps of emission line regions in the Milky Way, searches for tidal streams in the Galactic Halo, microlensing in the LMC, inter-galaxian populations in nearby galaxy clusters, QSO statistics, weak lensing studies, galaxy counts at redshifts out to z=2, searches for galaxy clusters, and cosmology with supernovae, to name a few projects.

The assigned time to the present Mosaic projects range from very large 5 year survey projects to much smaller 1-2 night pointed surveys, and we expect that DECam will be used in the same manner. The light grasping power of a 4m telescope is ideal for finding objects to be followed up on 8m telescopes either spectroscopically or in the near-infrared. These Mosaic imagers are often the first step in any scientific project requiring Gemini or Keck time. Because the suite of 4m and 8m class telescopes will not change significantly in the next 10 years, data products provided by 4m optical mosaic surveys will continue to be extremely important for the support of the largest aperture telescopes, as well as for stand-alone photometric projects.

The DECam, with a field 8 times the size of the present Mosaic cameras, and with a read time of only 17 seconds, will provide a much wider field and more efficient use of observing time. The initial filter suite will be the SDSS "griz" filters. Any present Mosaic filter can be put into the filter bolt (during the day) so that all present Mosaic projects can be continued with these filters. We imagine, however, that a number of other filters that use the full field will be constructed for important survey projects, funded outside of the present proposal. We anticipate that the user community will want to use the interference filters DDO51, an Hα set, [OIII], [SII], and Y (1 micron). Less expensive filters that users may need are the glass versions of the broadband BVR filters. However, we expect that the popularity of Johnson/Kron-Cousins filters will steadily decline over the next decade as more programs make use of SDSS databases.

In the following sections, we give a flavor of the wide range of science projects that will use the larger field and reduced read time of the DECam. As a regularly scheduled NOAO instrument, we expect that time on DECam will be assigned to projects in a similar fashion to the present Mosaic imagers - serving large surveys allotted time through the NOAO Survey TAC, as well as the traditional few night runs.

9.1 Stellar Science Cases

With DECam, CCD imaging moves further into the field of view regime previously accessible only through Schmidt cameras and photographic plates. For example, the CTIO 0.9-m Schmidt, now retired has a field of view of 5 degrees by 5 degrees. Such cameras have provided the basis for many directions of astronomical research, not least the exploration of populations and distributions of stars in our own and nearby galaxies. Such stellar astronomy is an obvious field in which DECam will find considerable use among the community.

-- Kuiper Belt searches

The Kuiper Belt is a region beyond Neptune containing tens of thousands of small bodies in orbit around the Sun. The KBOs allow us to study how dust grains in the early solar nebula coagulate into the planetesimals of the present epoch. The KBOs are fossil remnants of the chemical and dynamical processes that occurred in the outer solar disk at the time the Solar System formed. Their physical characteristics should tell us much about the formation of the circumstellar dust disks we see in external stars and directly tell us about the conditions of planet formation. A deep survey of the ecliptic will allow us to catalog a population of thousands of KBOs in terms of their dimensions, content, and dynamical characteristics. The statistics of such a survey will allow us to better understand the physical conditions at the time of the formation of the Solar System. A large number of KBOs will be available for spectroscopic follow-up at 8m class telescopes. Their thermal and bolometric properties can be followed up with SIRTF and ground-based mid-infrared imagers.

-- Proper motion surveys of galactic open clusters

Recent years have seen considerable progress in the identification of very low mass stars and brown dwarfs, particularly in open clusters. These systems contain stars of known distance, age and metallicity and make excellent laboratories for the study of stellar structure over the full mass range of stable, hydrogen burning stars. It is now possible to study the physics of coeval objects having masses that range over three orders of magnitude. Particularly interesting are the newly identified very low mass stars providing important insight into the study of lithium evolution, angular momentum evolution, spotting, variability, coronal activity, binary fraction and mass function. If one assumes that all disk stars originate in open clusters, then open cluster studies are relevant to the general field population

Since open clusters subtend generally large angles on the sky, the majority of work done on them has historically been via Schmidt plates. Membership is established through a number of means, but proper motion studies are prominent. DECam will be an ideal tool with which to pursue future studies, providing faster, more precise and deeper results than a photographic plate. Of course, this requires that DECam be an astrometrically stable instrument.

In this field and other explorations of low mass objects, DECam will be complemented by future wide-field IR instruments, which will permit confirmation of cluster members.

DECam's significant red sensitivity will be particularly useful for observations of the redder, lower-mass cluster members.

-- Cool white dwarfs

The low-luminosity fall-off and the general form of the luminosity function of white dwarfs is an important new tool for dating and exploring the history of star formation in the Galaxy. The coolest white dwarfs represent the graveyard of the very first stars to have formed in the Milky Way, now slowly fading into thermal oblivion. It is believed that these objects are significant contributors to Galactic dark matter, being found in microlensing surveys such as MACHO+EROS. Finding these objects is a job for large surveys and DECam is ideally suited.

Such a project may require investment in additional filters beyond those planned for the Dark Energy Survey, e.g. DDO51 which separates the white dwarfs which are essentially featureless at 515nm, whereas other stars generally show significant absorption.

-- Globular cluster tidal streams

Recent years have seen the discovery of streams of stellar debris emanating from Galactic globular clusters and nearby dwarf galaxies as a result of the tidal stresses they have experienced in passage through the three dimensional gravitational potential field of the Milky Way. Clearly such tails provide invaluable probes of this potential field and details of its interaction with the source clusters and galaxies. Because these streams extend over several degrees of arc, or more, DECam will inevitably see use in their study.

-- Variable stars

Stellar variability in all its forms is an important phenomenon in the study of stellar astrophysics. From simple binaries, through pulsating and flare stars, to interacting systems, all aspects of the physics of stars are open to study, indeed many can only be studied through photometric variability. DECam, with its fast readout gives it great potential as the world's largest time series photometer. Volume-limited variability surveys on time-scales of a few minutes is still a relatively untouched region of the parameter space of ground-based astronomy and should offer a rich mine for our understanding of the space densities of numerous types of variable stars and through this, of stellar evolution in general.

To select a quick example, a single pointing of DECam near the Galactic plane might be expected to contain as many as several hundred cataclysmic variables (depending on which estimate of the poorly known space density one believes) which amounts to a significant fraction of the number of such systems currently known. A series of short exposures of such a field will generate a vast number of light curves from which the cataclysmic variable systems can be identified through their flickering -- a stochastic variation on time scales of seconds to tens of minutes resulting from the interaction of the material accreted from the late-type star in the system with the accretion disk surrounding the white dwarf component. It goes almost without saying that the same kinds of variable survey data will also expose planetary transits and permit the discovery of new extras solar planets.

-- Space astronomy follow-ups

Finally, ground-based optical surveys have always been vital in the identification of the sources discovered during space-based surveys in other regions of the electromagnetic spectrum. In particular, X-ray surveys provide large numbers of objects which require optical follow-up. Currently, the Blanco telescope and Mosaic II are seeing use for following up on the Chandra Observatory surveys, such as the ChamPlane campaign to identify serendipitous sources in the Galactic plane, concentrating particularly on X-ray binaries and cataclysmic variables. Future missions, such as Constellation-X, will have similar needs, which will be adroitly addressed with DECam.

This is another use of DECam which could benefit greatly from the availability of filters besides those of the DES. Specifically, X-ray follow-up and variable star surveys will likely offer some demand for an H-α filter. Preliminary examination of the current corrector design implies it is sufficiently telecentric to allow the use of reasonably narrow filters. Presumably, any filters for DECam use other than for DES will have to be purchased through third parties and sources such as NSF proposals, but this is not an unusual method of facilitating a specific observing program at NOAO.

9.2 Extragalactic Science Cases

-- External stellar populations.

The DECam will be an excellent imager for studies of the stellar populations of the Magellanic Clouds. With a field of view 2.2 degrees in diameter, the DECam will cover the main body of each galaxy in a few pointings. Two science cases can be addressed with the DECam: the stellar population of the LMC/SMC region and the search for microlensing in the halo of our Galaxy.

The recent LMC Stellar Catalog by Zaritsky and collaborators done with the LCO 1m Swope telescope covered 64 sq-degree to a completeness level of V=20. The DECam can cover the same area in 21 pointings. We anticipate a community survey project targeting both galaxies and the extended regions around each galaxy including the bridge between the galaxies. In uncrowded regions, the photometry can reach m=26 to allow for searches of faint tidal streams that should be associated with the multiple passages of both galaxies around the Milky Way. A very deep search into the possible halos of these galaxies would extend to 10 degrees from the galaxy center. The whole halo of each galaxy could be covered in 100 pointings with the DECam. Such a survey would be prohibitive with the present Mosaic imagers.

The SuperMacho program for microlensing of Galactic halo stars on the screen of LMC stars covers 18 sq-degrees. The SuperMacho program has a 5 year survey mission to find lensing events with 30 half-nights each year. Each field is revisited every second night in a single color. The present microlensing search is limited by the field size and read time of the CCD. The DECam would much more efficiently cover the LMC to greater depths. The present SuperMacho search expects to find 10-20 events per year with coverage every 2 days using half nights. The same search could be done in less than 1 hour per night with DECam in two colors instead of one. With two colors, microlensing (which is achromatic) can easily be separated from other transients. With coverage every night for one hour, one could increase the chance of finding cusping events, which would indicate binary or planetary companions.

As with the Macho and SuperMacho projects, the database for the microlensing survey provides a rich hunting ground for other projects, especially those interested in time-varying phenomena.

-- Microlensing toward the Fornax Dwarf Galaxy

The DECam can cover the Fornax Dwarf in a single pointing. A routine survey of Fornax every few nights over a few months per year with single pointings will determine the Galactic halo lensing rate toward this object. With microlensing rates toward Fornax, M31, the LMC, and the SMC, a spatial distribution of dark compact objects in the Galactic halo can be determined. Present estimates are that up to 20% of the dark matter Halo is composed of compact objects, but whether this population conforms to the flattened spheroid potential of the Halo has not been determined.

-- Dwarf galaxy searches in nearby galaxy groups

While much attention has been focused on large clusters of galaxies, most galaxies in the Universe exist in the field or in loose groups, such as the nearby Sculptor, Cen A, NGC 2997, M66, and M96 groups. Hierarchical clustering predicts large number of dwarf galaxies of unknown luminosities in these groups. The number of dwarfs should be factors of 10 to 100 times the number of brighter galaxies. The search for these dwarfs requires extremely deep and wide field searches for very faint red galaxies with spheroidal structure, analogous to the Milky Way and Andromeda satellite Sph galaxies.

-- Intra-cluster light (ICL)

DECam would be able to image intra-cluster light in nearby galaxy clusters. This is the very low surface brightness signature of stars that seem to be associated with the clusters themselves, as opposed to any one galaxy, though the origin of the stars is an open question: were they formed along with the cD galaxy or in the intracluster medium, or are they the remnants of other stripped/disrupted galaxies? Studies of the spatial distribution and color of the intra-cluster light helps to pin down the origins. The distribution of the light can also be used as a tracer of the halo potential and mass to light ratio.

The DECam would also be an excellent imager for finding PNe in nearby clusters. These surveys need large apertures and large fields to go very deep in a [OIII]5007 filter, but also cover as much of the nearest clusters as possible. These tracers could probe even further from the cluster center than diffuse light to trace the spatial distribution of the intra-cluster population. The KAOS instrument at Gemini south could be used to get spectra for the kinematics of the population to compare with the ICL. In particular, is the ICL population relaxed compared to the galaxy distribution?

In both projects, the large simultaneous area allows for deep studies of nearby (and consequently angularly large) galaxy clusters. For the diffuse light, the simultaneous coverage helps reduce the systematics in the measurements, which dominate at these low surface brightness levels. In addition, it is critical to image the cluster with a field significantly larger than the cluster so that the cluster light can be measured relative to blank sky

-- Photometric surveys of the high redshift universe

The DECam would be well suited for intermediate depth, smaller solid angle extragalactic surveys as a complement to the DES. These surveys could complement ongoing surveys by pushing to larger solid angle than is possible with current generation cameras. This is especially important if one wishes to study the clustering of galaxies and its redshift evolution, and large solid angle, deep photometry is also critical for any program that seeks rare, faint objects, such as quasars beyond a redshift z~6.

9.3 DES Legacy Archive Science

Besides the results from the key science programs proposed by the Dark Energy Survey team, the data archive will be the rich resource for the community. The DES Legacy archive and the user community science image archive will become a major digital sky survey; the most extensive in the Southern Hemisphere until LSST is built, assuming it goes in the south. The DES data, with uniform depth and coverage, will be well suited for fundamental astronomical studies - parallaxes, Hess diagram analysis, and the like. Even in the era of the LSST, the DES data will be useful for proper motion studies and other time domain studies. We realize that the utility of the archive to the community will depend on its accessibility and the robustness of its calibration; we have designed a survey strategy to meet the calibration requirements for the data (see Chapter 3 for requirements and Chapter 4 for the survey plan), and we have developed a data management and archiving plan with the goal of rapid community data release and ease of community access (see Chapter 6).

Some of the topics listed in the previous section would benefit from the DES archive, but in addition, there are additional projects. Here we describe in detail two specific examples of doing science using the DES Legacy archive: cluster strong lensing and wide ranging quasar science

-- Strong lensing in galaxy clusters

The incidence of arc formation due to extreme strong-lensing by galaxy clusters has long been suggested as a cosmological probe. Extensive research in the 1990's, exploiting primarily the X-ray selected EMSS cluster sample, demonstrated modest consistency between observations and theoretical predictions for open low-Ω_M cosmologies. Since this work, which culminated in the analysis of Bartelmann et al. (1998), there has been a growing realization that the predicated arc statistics are in rather gross disagreement with the flat, Λ-dominated cosmology indicated by many other probes.

The formation of arcs is dependent on essentially three things: 1) the cosmology, 2) the source population, and 3) the properties of the lenses (clusters). The cosmology will be well determined by the DES itself, and the source population is now relatively well known with further progress to be expected from follow-up of surveys such as the Hubble Ultra-Deep Field. A large sample of clusters with arcs could then be used to understand the (dark) mass structure of galaxy clusters independent of the luminous component of the cluster.

How many arcs might we expect to see in the DES? Statistics are scarce, but the most comparable dataset is the ~90 square degrees of RCS data, which yielded 7 arcs around 5 clusters. The DES data are in more and bluer bands (and hence likely to pick up more arcs, because arcs tend to be blue) and typically about 0.5 mags deeper than the RCS. One can thus readily expect several factors of two gain in finding arcs in the DES over the RCS. The DES has similar redshift grasp to the RCS, and is about 55 times larger in area. It is thus reasonable to expect to find something like 1000 strong-lensing clusters in the DES! Such a sample would completely revolutionize our understanding of cluster structure and could present a very powerful cosmological test in its own right.

Finally, it is worth noting that most of the strong lensing by clusters does not result in arcs, but multiple images which may not be morphologically recognizable despite being highly magnified. A particularly striking case of this is the object cB58 (Yee et al. 1996) which is a 20th magnitude galaxy at z=2.6. The multi-filter observations of the DES will allow us to recognize such objects as extreme outliers in magnitude-redshift space, which are on lines-of-sight behind massive clusters. Given the area of the DES we expect to find perhaps hundreds of such objects, which will be a profoundly important sample for studying the very distant universe and the formation of galaxies.

-- QSO catalogs

Wide, multi-band imaging surveys provide incredible resources for improving our understanding of the Universe. The Palomar All-Sky survey, 2MASS, and the Sloan Digital Sky Survey enabled advances in optical astronomy, as radio, X-ray, and gamma-ray surveys have done in other wavelengths, by taking advantage of unique qualities that large quantities of data offer: ability to find rare, exotic sources and reduction of uncertainties in statistical distributions due to reduced Poisson fluctuations.

Other "large" statistical samples of QSOs have been compiled by:

– SDSS -- 8,000 square degrees to a limiting magnitude of 20.1 for 80,000 spectroscopically-confirmed QSOs when SDSS is completed. From the imaging SDSS data alone, a catalog of photometrically-identified quasars to a limiting magnitude of 21 has 100,000 QSOs in 2099 square degrees (Richards et al. 2004). The highest-redshift QSOs ever discovered (up to z=6.4) are also from the SDSS, with spectroscopic follow-up from other instruments.

– 2dFQ -- 750 square degrees to a limiting magnitude of 21 for 49,425 spectroscopically-confirmed QSOS.

– COSMOS -- 2 square degrees, with 600 QSOs to 24th magnitude and multi-wavelength observations

– COMBO-17 -- 1/4 square degrees, with 100 QSOs to 24th magnitude, but with precision photometric redshifts (good to 0.015 in z) from narrow-band filters. (Wolf et al. 2004)

– GDDS -- 0.1 square degrees, to 26th magnitude (but with extensive coverage in many wavelengths)

In comparison, the DES will carry out a quasar survey -- during the course of normal operations -- covering 5,000 square degrees, to 24th magnitude, including 1.6 million photometrically-identified QSOs.

Clearly, this unprecedented data sample opens up new vistas:

1. The highest redshift quasars: covering an area comparable to the SDSS, but 4 to 5 magnitudes fainter satisfies the criteria of Fan et al. (2004 ASP Conference Series v311): "A deep quasar survey at z ~ 6 is needed to understand the complete picture of high-redshift quasar evolution and its relation to reionization history." The SDSS has tentatively found evidence of reionization at z ~ 6 (Becker et al. 2001) and the DES should image many more high-redshift quasar candidates than the SDSS, testing this reionization claim and potentially mapping the surface of reionization, and probing coevolution of AGN, black holes, and QSOs.

2. The catalog of quasar candidates identified in the 4-filter photometry will have photometric redshifts determined to ~0.15, and a probability vs. redshift distribution to quantify ambiguities. Cross-correlation of this catalog with X-ray and radio surveys, and spectroscopic follow-up with multi-fiber spectrographs, are fertile research programs. The large numbers allow us to study the evolution of the luminosity function with redshift and absolute magnitude.

3. We estimate the number of quasars in the DES by assuming a faint-end slope of the QSO luminosity function of around 0.3. However, the distribution of quasars is itself

rather uncertain, especially at fainter magnitudes and higher redshift. At around g ~ 21 the redshift distribution flattens; the DES could unambiguously determine whether this is due to survey incompleteness or intrinsic to the population of faint quasars.

4. The clustering of quasars alone provides a wealth of cosmological information (see, e.g., Outram et al. 2003). Relationships between the clustering of quasars along and perpendicular to the line-of-sight provide a strong constraint on the Dark Energy (the Alcock-Paczynski effect), while the relative angular correlation of the quasar and galaxy populations can provide a constraint on the matter density via the skewness statistic, without the need to measure accurate population redshifts (Menard, Bartelmann, & Mellier 2003). While many of these tests may be augmented with spectroscopic redshifts, photometric redshifts often provide sufficient information, especially in conjunction with ancillary data in other passbands (such as might be obtained in conjunction with VISTA).

5. Lensed quasars offer a unique view of the distant Universe. Knowing the number of faint quasars is critical to understanding the effects of lensing magnification bias. Assuming typical cosmological models, the DES should identify around 50 strongly lensed QSO pairs (as well as quadruples, sextuplets, etc.) with separations less than 10 arcseconds (see, e.g., figures 7-15 of Lopes & Miller 2004). The actual number of lenses found can by itself constrain cosmological models, subject to uncertainties in halo modeling, in addition to the constraints on the Hubble parameter that arise from measuring image delays between lensed pairs.

6. The general DES dataset also provides important information on the variability of quasars, via the repeated observations over the course of the survey used to build up the entire 5000 square degrees. The smaller, supernova-focused area, however, would prove even more useful in this regard due to the large number of epochs sampled over a number of years to faint magnitude limits. Variability is proving to be a powerful method for selecting quasars, at a range of redshifts (see, e.g., Rengstorf et al. 2004). The SN component of the DES should provide highly-sampled light curves (as short as 1 day in the observed frame) for around 20,000 quasars. This information can be used to constrain the mean lifetime of quasars (e.g., Martini & Schneider 2003) as well as the power spectrum of accretion that constrain models of accretion disk instabilities (Vanden Berk et al. 2004).

In addition to the strides that will be made with this QSO sample, we expect that the astronomical community could request that imaging be taken with narrow-band filters.

9.4 Community Workshop

The limited sample of science cases listed above is based on the scientific range of interests of the writers of this proposal. The US astronomical community, however, can tell us much better what is the true range of science that the DECam instrument can support. As part of the Dark Energy Survey proposal, we will call for a workshop to be held for prospective users of DECam and the DES Legacy archive. This workshop will be held in 2004 or in early 2005, preferably near the Chicago area so that most of the

DES team can attend. It would be preferable to hold the workshop before the end of the year 2004.

The goals of the workshop are twofold. We want to hear from the community about their ideas for the science that can be done with this instrument. In addition, the DECam project and NOAO need to anticipate instrumental functions and data products not covered in this proposal. For instance, what should the form of the archive be? What data products are crucial to include in the archive? What are the most important filters that need to be acquired? What should be the role of large surveys versus smaller pointed surveys? We imagine that users will suggest novel ways to use the instrument in a manner we have not anticipated. Can these novel techniques be incorporated into the user program as run by NOAO without impacting the cost, operation, and science of the Dark Energy Survey? What will be the preferred community access to the telescope and instrument during the time of year the DES is running?

We can expect the unexpected from a community of astronomers presented with a world class instrument on a mature telescope.

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