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NETWORKED ASTRONOMY AT APACHE POINT OBSERVATORY

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ABSTRACT

We propose to initiate a project to implement a fiber optic network at Apache Point Observatory such that the existing (and future) spectrographs on site can be supplied with target light from any of four telescopes. The first phase of this implementation will be to develop the site infrastructure to connect all of the telescopes through the addition of a new utility pathway running from the ARC 3.5m past both of the small aperture telescopes and terminating at the SDSS telescope. This will be accomplished through a combination of below-ground conduits, above-ground cable trays, and existing cable routing paths available at each telescope. This infrastructure will be used to implement a fiber run between the SDSS/APOGEE spectrograph, the ARC 3.5 m telescope, the ARCSAT 0.5 m telescope, and the NMSU 1 m telescope. We propose to route 270 of the 300 available APOGEE fibers to the TR1 bent Naysmyth port of the 3.5 m telescope. Of these 270 fibers, 217 will be grouped together to form a integral filed unit $\sim 32''$ size on sky. The remaining 53 fibers will be placed outbound of the IFU to sample sky. The combination of the 3.5m aperture and the APOGEE spectrograph used as an integral field unit will open exciting new science opportunities at a relatively low cost for the capability, leveraging the existing APOGEE instrument. The remaining 30 APOGEE fibers will be routed to the two small aperture telescopes, with 15 fibers going to the focal plane of the ARCSAT 0.5 m telescope for a future instrument application and the remaining 15 will be routed to the focal plane of the NMSU 1 m telescope where they will replace and improve the existing fiber run.

1. INTRODUCTION

Apache Point Observatory (APO) in southern New Mexico hosts four research telescopes: the ARC 3.5 m (Siegmond et al, 1984), the 2.5 m SDSS telescope (York et al. 2000), the NMSU 1 m, and the ARCSAT 0.5 m. Table 1 gives the basic native perimeters for each of the four telescopes on site. These telescopes are spread across 100 m of ridge line in the Sacramento Mountains, starting in the north with the ARC 3.5m and proceeding to the south to the NMSU 1 m, ARCSAT, and finally the SDSS 2.5 m (Figure 1). These four telescopes operate independently with the notable exception of a proof-of-concept fiber run between the SDSS/APOGEE spectrograph and the NMSU 1 m telescope. The ARC 3.5 m and the ARCSAT telescope are both subscription based telescopes available to the ARC users community. The NMSU 1 m is owned and allocated by New Mexico State University: currently there is an ongoing collaborative project to use a fraction of the time with the SDSS/APOGEE instrument to support the SDSS project. The 2.5 m SDSS telescope is a wide field survey telescope used currently for three long (6 year) duration spectroscopic surveys; eBOSS, MaNGA (Bundy et al, 2014), and APOGEE-II (Wilson et al. in prep.).

Existing spectroscopic instrumentation at APO is currently only available on the ARC 3.5 m and SDSS telescopes. On the ARC 3.5 m, the suite of spectrographs includes DIS, TripleSpec, and ARCES. DIS (Dual Imaging Spectrograph) is a two channel long-slit ($\sim$ 6 arcmin) optical spectrograph operating at $\lambda = 350$ - 900 nm with a resolution of $R \sim 1000 - 4000$, depending on the choice of grating. TripleSpec is a medium resolution near-IR spectrograph operates at $\lambda = 0.95$ - 2.46 μm with a resolution of $R \sim 2500, 2800, or \sim 3500$ depending on the slit configuration. The permanently mounted high resolution echelle spectrograph ARCES operates from $\lambda =$ 320 -1000 nm with a resolution of $R \sim 31,000$. All three of these spectrographs accept the native f/10 beam from the 3.5 m telescope and are optimized for this plate scale. The SDSS 2.5 m telescope has two multi-object fiber-fed spectrographs: APOGEE and BOSS. Both spectrographs are used in survey mode. The APOGEE spectrograph (Wilson et al, in prep) is a near-infrared $\lambda =$ 1.51 - 1.70μm, fiber-fed, multi-object (300 fibers), high resolving power ($R \sim 22,500$). The BOSS spectrograph (Smee et al. 2012) accepts 1000 to 1500 fibers split between two identical spectrographs operating at $\lambda = 350$ - 1100 nm spectrograph operating over two channels with a resolution of $R \sim$2000. Both spectrographs use a $2''$ (120 μm) core fiber and are configured to accept an f/4 beam.

The close proximity of the four telescopes allows us to consider fiber optic links between each telescope and instrumentation at any of the other telescopes. Such an implementation would open up huge potential for new science for all users by increasing the availability of high quality spectroscopy on the small aperture telescopes as well as adding the possibility of integral field or multi-object spectroscopy at the 3.5 m telescope. Of the spectrographs on site, the fiber-fed spectrographs of the 2.5 m offer the simplest coupling to the other 3 telescopes on site. A simple focal reducer can be used to modify the input of the slower telescopes to match the expected f/5 input of both the BOSS and APOGEE spectrograph.

While all of the time on the 2.5 m is allocated for the

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TABLE 1
Summary of APO Telescope Peramitors

Telescope	Diameter (meters)	f-ratio	Field of View ′	Plate Scale ″/mm
ARC 3.5m	3.5	10	9.5 *	5.8
NMSU	1	6	15.7	34.1
ARCSAT	0.5	8	32	51
SDSS 2.5m	2.5	5	180	16

*Field of View can be increased with a change to existing baffling

SDSS-IV projects between July 2014 and July 2020, both spectrographs are not in use at all times. eBOSS operates for roughly half of the available dark time and uses only the SDSS optical spectrographs. MaNGA operates during the other half of the dark time using the optical spectrographs; however, while MaNGA observes, APOGEE spectrograph is used for co-observing. During fully bright time, only the APOGEE spectrograph is used. As a result, the APOGEE spectrograph is idle roughly 25% of the time (in dark time), and the SDSS optical spectrographs are idle roughly 25% of the time (in bright time).

Of the two fiber-fed spectrographs, the APOGEE near-IR spectrograph offers the most potential for long runs of fiber between telescopes because of the better throughput of fibers in the near-IR as compared to the optical (see section 3.2.3). In addition to the low attenuation at the APOGEE wavelengths, this spectrograph is also configured with with quick change couplings called *Gang* connectors. These allow for a ready made switching point between different telescopes and the APOGEE instrument. The combination of low fiber attenuation, ready made switching couplings, and convenient f-ratio make the APOGEE spectrograph a clear choice to be the first networked instrument at APO. This is the proposal discussed here.

The remaining spectrographs on site could be integrated into the fiber network based on use demand and complexity of interface. The fiber pathways proposed here will be sufficiently large that any number of combinations of instruments and telescopes could be achieved in the future. All that would be needed is appropriate f-ratio modification at the input and output of the fiber and the fiber run itself.

Note that the cost associated with networking the APO site is primarily in the installation of new utility trenches and cable trays. The cost to do so is small as compared with the multi-million dollar cost of the APOGEE instrument itself, so this opportunity provides a way to leverage a much larger investment of money to get increased scientific capability.

The remainder of this document will focus primarily on the infrastructure changes required to enable observations using the APOGEE spectrograph with the ARC 3.5 m, ARCSAT, and NMSU telescopes. Section 2 lays out some potential scientific projects that would be enabled by such a link. Section 3 discusses the proposed fiber network and its expected performance. Section 4 discusses the implementation of a fiber link to the APOGEE spectrograph from the other telescopes. Section 5 presents a budget for the project.

2. SCIENCE JUSTIFICATION

A number of potential scientific uses of a fiber feed to APOGEE from the APO telescopes have been expressed. The range of possible projects depends on the configuration of a proposed fiber-feed. The simplest configuration would enable observations of single objects only, and this is what is proposed for the 1 m and 0.5 m feeds. At the 3.5 m, a simple implementation would be a single fiber bundle with some outlying sky fibers. In the native f/10 beam, a single fiber would subtend 0.71”, and a 217-element fiber bundle (as discussed below) would cover an area with diameter $\sim$ 20 arcsec with a fill factor of $\sim$ 50%. However, using a microlens array in front of the fiber bundle for focal reduction to match the f/5 beam that is provide for in the APOGEE spectrograph would increase the FOV to $\sim$ 39 arcsec across with nearly 100% fill factor. More complex options would be for multiple smaller fiber bundles spread over a larger area, or fully configurable distribution of individual fibers or small fiber bundles.

2.1. *Individual object projects*

2.1.1. *GAIA followup (Holtzman)*

One application might be observations of stars identified as subgiants once GAIA parallaxes become available. The great advantage of subgiants is that, with known distances, accurate ages can be determined. Ages in conjunction with the chemical abundances provided by APOGEE spectra provide a powerful tool for studying Galactic evolution. Subgiants are intrinsically fainter and bluer than the giants that are the targets of the main APOGEE survey. At M(H) 2, the 3.5m feed would be able to get good abundances to a distance of 2 kpc. Of course, to build up a sample of a reasonable number of stars, one at a time, would require a significant amount of observing time.

2.1.2. *B[e] stars (Chojnowski)*

Another application might be a survey of B[e] stars, which are B-type emission line stars that differ from classical Be stars due to the presence of forbidden emission lines and strong IR excesses. These features are attributed to a circumstellar dust component not present in the case of classical Be stars. The 100 or so known B[e] stars are a heterogeneous group often found to be supergiants (sgB[e]), pre-main sequence (HAeB[e]), or compact planetary nebulae (cPNB[e]). However, the fact that 50% of them remain unclassified (unclB[e]) is a testament to the complexity and richness of the emission line spectra, and also to the difficulty of conducting a uniform survey given the isolated nature of the stars. On average, B[e] stars are almost 4 magnitudes brighter in the H-band than in V-band, making them ideal targets for NIR spectroscopy (Lamers et al. 1998) and (Miroshnichenko et al. 2007AB).

2.1.3. *Supergiants (Levesque)*

Combining the APOGEE spectrograph with the 3.5-m telescope would allow the study of red supergiants (RSGs) in the spectral regime where their SEDs peak, an improvement over most current work being done in the optical. This set-up is ideal for obtaining high resolution H-band spectroscopy of RSGs in M31, allowing us to test atmosphere models in the IR and develop IR-focused spectral diagnostics for properties such as spectral type, effective temperature, and surface gravity.

In addition, H-band spectra of a large sample of yellow supergiants (YSGs) in our own Milky Way is another compelling application of this set-up. These massive stars represent one of two rare stages in post-main-sequence massive star evolution, moving from the blue supergiant to RSG stage or, in more massive cases, transitioning from RSGs into Wolf-Rayet stars. Spectral signatures in the IR (including changes in mass loss rates distinguishable with high resolution spectra, or dust production through episodic stellar winds) offer one potential means of distinguishing between YSGs in these two states. Establishing such a diagnostic and applying it to Milky Way YSGs would offer a valuable new means of quantifying the transitional phases of post-main-sequence massive star evolution. This allows us to rigorously test new models of massive star evolution and eventually extend this technique to IR spectra of yellow supergiants in other Local Group galaxies using future facilities such as JWST.

2.1.4. *Eclipsing binaries (Hebb)*

Another project is to obtain double-lined RV curves for a large sample of G+M dwarf Eclipsing binaries. There exists a large sample of such objects. Right now, most of them are single-lined EBs, and these have been analyzed as if they were transiting planets so we need an external constraint on the primary star mass. However, with high S/N NIR spectra, we could see the cross-correlation peak of the secondary component and turn these SB1s into SB2s. The M dwarfs in the sample range in mass from 0.5 - 0.15 Msun. Obtaining direct mass and radius measurements for a large sample (50-100) M dwarfs in this mass range and obtaining their metalliticies from the standard analysis of the G-dwarf spectrum in the pair is an important project for upcoming transiting planet missions that target M dwarfs. We will need to be able to relate optical or IR colors or magnitudes of the M dwarfs to their masses and radii in order accurately characterize any planets that are orbiting these stars.

The full range of magnitudes is V 9-13, but the vast majority are V 10.5-12.5. The G-dwarf dominates the brightness, so the V-K 1.5, so targets are K 9-11. The flux from the secondary is very low, so we do need high S/N in the IR to see the secondary spectrum in the CCF.

2.1.5. *Radial velocity monitoring (Troup)*

The APOGEE spectrograph provides radial velocity precision to $\sim$ 100 m/s. During the course of the SDSS/APOGEE surveys, a number of substellar companion candidates have been identified using multiple SDSS/APOGEE observations, but full characterization of these requires additional followup, for more RV points, so a fiber link would potentially be useful to people interested in substellar companion candidates identified by APOGEE. Having RVs from the same instrument is certainly preferable to RV followup using alternate instruments.

2.1.6. *Follow-up classification of SPIRITS & LCOGT detected luminous variables and IR-transients in the nearest 200 galaxies (Bally)*

A large multi-year program on the Spitzer warm mission, the SPitzer InfraRed Intensive Transients Survey (SPIRITS) let by Dr. Mansi Kasliwal (Carnegie) is discovering luminous IR-only transients in 200 nearby galaxies. This program has been awarded over 1,000 hours of time during Spitzer's warm mission phase and has found several dozen infrared-only transients with 3.6 to 4.5 μm absolute magnitudes between -11 and -16. While some of these objects may be supernovae either buried in dense molecular clouds or located behind high opacity clouds, others may trace new phenomena such a the merger of stars in compact binaries similar to V838 Mon in the Milky Way, or high-luminosity eruptions associated with the birth of massive stars similar to the 10^{48} erg event thought to have occurred behind the Orion Nebula $\sim$500 years ago which produced the spectacular 'Orion Fingers' of shock-excited H_2 and [FeII] emission and ejected at least three massive stars (Bally et al. 2011).

The APO 3.5 meter equipped with an IFU connected to APOGEE could be used to classify both the transients (if detected in the H-band) and the surrounding starfield to determine the nature of the surrounding stellar population - old stars or young OB associations or star clusters. Even though this SPIRITS program may not be around by the time the APO fiber network is built, similar synoptic programs may be in place using LSST PanSTARS and other facilities.

2.1.7. *RR Lyrae stars*

A significant goal of the SDSS/APOGEE2 project will be to obtain high-precision radial velocities of a large number of bulge RR Lyrae stars. To account for the RV variability of these stars, time series of a set of calibrating RR Lyrae stars will need to be done to characterize the RV curves in the H band, possibly as a function of RR Lyrae type. The brightest RR Lyraes are accessible with the 1m telescope feed to APOGEE, but it is possible that a larger aperture will be needed to fully satisfy the requirements to sample a broader range of RR Lyraes. The study of the behavior of RR Lyrae atmospheres as traced in the H-band is also of interest in its own right.

2.1.8. *Calibration*

Validation of metallicity determination from IR spectra is critical to ensuring the success of projects like APOGEE, including future IR spectroscopic projects. Much of this can be accomplished by observing stars in the IR with well-measured abundances from optical spectra. Such stars are often spread across the sky and are perhaps not well suited to APOGEE observations in survey mode. The brightest of these stars are well-suited to individual-star observations using the 1m feed. Fainter stars would be well-suited to individual star observations using the 3.5m,

2.2. *Integral field projects*

2.2.1. *Nearby Galactic star and star cluster formation (Bally)*

Tens of thousands of young (< 10 Myr) stars are located within the forming star clusters and OB associations located within a few kpc of the Sun. Most form in compact, sub-parsec groups containing dozens to hundreds of potential targets can fit within the 9′ FOV of the 3.5 meter Nasmyth ports. Examples include the Orion Nebula Cluster (ONC), NGC 1977, OMC2, OMC3, L1651N clusters in Orion A, the NGC 1333 and IC 348 clusters in Perseus. These groups contain between 100 and 1,000 stars, dozens of [FeII] bright outflows, and shocks.

High-spectral resolution studies of young cluster members will results in several types of measurements which will greatly advance our understanding of the formation and early evolution of low-mass T TTauri stars and intermediate mass Herbig AeBe (HAeBe) stars and their forming planetary systems. As these stars accrete their mass and clear their birth environments, the peak of their spectral energy distributions (SEDs) evolve from the submillimeter, though the mid-IR, the near IR, and visual parts of the spectrum as they evolve through the Class 0, I, II, and III stages of young stellar object (YSO) classification into classical T Tauri (CTTs) and weak line T-Tauri (wTTs) stars. This process takes anywhere from 1 to over 100 Myr depending on stellar mass (moderate mass stars evolve fast while lower mass stars take longer to evolve through these stages). Although the SEDs of the youngest stars peaks in the far-IR to sub-mm, outflow cavities often provide windows through which near-IR, and sometimes even visual light, and emerge.

Accreting YSOs power spectacular jets and bipolar outflows which produce strong forbidden line and hydrogen recombination line emission in the visual and near-IR. The strong [FeII] 1.644 μm emission line falls into the APOGEE band.

Forming stars are irregular variables which undergo occasional flares triggered by episodic but catastrophic accretion events. Flares range form a few magnitudes lasting a few months to years for the so-called EXOr stars (named after the prototype, EX Ori) to 2 to 10 magnitudes events lasting years to decades for FUOr stars (named after the prototype, FU Ori).

An IFU containing hundreds of fibers can be use to efficiently measure the radial velocity field of the shocks and jets using the 1.644 μm [FeII] line to trace radial velocity structure of Herbig-Haro (HH) jets, map HH object kinematics in moderately embedded regions with AV < 10 magnitudes. Centroiding line profiles will enable radial velocity and velocity determination to a 1 to a few km/s. New science enabled by a multi-fiber / multi-object capability on the APO 3.5 meter includes:

• Spectral classification of YSOs using the H-band spectral signatures. The widths and shapes of photospheric spectral lines indicate surface gravity and rotation rates and can be used to constrain luminosity class and evolutionary stage. Although young clusters have high spatial density, contamination from background of foreground stars can confuse cluster membership, especially along the Galactic plane. Radial velocities, combined with various signatures of youth such as variability, presence of emission lines, veiling, and IR-excess emission determined from J, H, K or Spitzer and WISE photometry can be used to separate cluster YSOs from unrelated main sequence or post-main sequence contaminants.

• Precision radial velocity measurements using photospheric absorption lines to determine cluster velocity dispersions, and the radial velocities of individual members. Multi-epoch synoptic observations will enable the detection of invisible massive companions which are too embedded in their circumstellar environments or too close to their visible companions to be resolved in imaging surveys. Research on YSOs over the last two decades has shown that most stars are born in non-hierarchical multiple systems which experience chaotic small N-body interactions and dynamic decay. The formation of compact multiples in such N-body interactions and the ejection of the lower mass members results in the observed spectrum of single stars (most low-mass stars are single) and multiple systems (most massive stars are in multiples).

• Search for outflow signatures from young stars using the [FeII] emission lines. Many YSOs drive small-scale outflows and jets which can not be detected in images. Doppler-shifted or broad emission lines, especially from [FeII] in the H-band provide a powerful tracers of outflow activity. The H-band provides a great advantage in the study of YSOs because the extinction is much lower in the H-band than in the visual. High spectral resolution is essential for the removal of the bright OH airglow which hampers narrow-band imaging. The OH airglow increased the sky surface brightness by about 5 magnitudes compared in a typical 1% bandpass filter compared to the continuum level measured between the airglow line (Sullivan & Simcoe, 2012).

2.2.2. *[FeII] nebular kinematics (Bally)*

In addition to serving as a probe of spatially unresolved outflows from forming and young stars, the 1.644 μm [FeII] transition is an excellent tracer of shocks in spatially extended nebulae. The 1.644 μm [FeII] line is seen in protostellar outflows and jets (Herbig-Haro objects), expanding stellar wind bubbles and photo-ionized nebulae, proto-planetary nebulae, planetary nebulae, and supernova remnants. An IFU on teh 3.5 meter feeding the APOGEE spectrograph will provide a unique, high-spectral resolution capability for the measurement of the radial velocity structure and lone-of-sight velocity dispersion of spatially extended shocks. Because the extinction at 1.644 μm is about 10 times lower that at visual wavelengths, this line can be used to map regions too obscured to study at visual wavelengths. The high spectral resolution is needed to remove the bright OH airflow lines. To date, such studies have only been conducted for a handful of bright nebulae using slit-scanning with long-slit high-R spectrometers, and in a few cases IFUs. Examples of targets for which [FeII] kinematic mapping would produce new science include PNe, SNe, WR-star and LBV-like envelopes (e.g. NGC6888 or P-Cygni), and some RSGs.

2.2.3. *The nature of stars and clusters in the central molecular zone (CMZ) and nearby starburst galaxies (Bally)*

The CMZ contains the highest pressure and densest ISM in the Galaxy and may serve as a template for starbursts galaxies and high-redshift star formation. The Spitzer Space Telescope has revealed a large population of compact sources whose SEDs peak around 24 microns which tend to avoid the densest star forming clouds. If they represent recently formed massive stars (MYSOs), as proposed by Yusef-Zadeh et al. (Yusef-Zadeh, et al, 2009), their numbers would imply a large star-formation rate (SFR) in the CMZ. However, if many are found to be post-main-sequence red-supergiants (RSGs as suggested by An et al. (An et al, 2011) or main-sequence (MS) stars in unusually dense regions of the CMZ ISM (Koepferl et al. 2015), their older ages would imply a much lower SRF, in violation of the commonly used Schmidt-Kennicutt prescription ("star-formation-law") of SFR on gas surface-density. APOGEE high-R spectroscopy can be used to classify those 24 micron compact sources which have H-band counterparts (many of the ones not associated with dense gas are visible in

2.2.4. *Young Massive Clusters (YMCs) and Super Star Clusters (SSCs) (Bally)*

The APOGEE IFU on the 3.5 meter be used for studies of textreme starburst environments found in galaxies to probe the internal velocity dispersion, center of mass radial velocity, and stellar make-up of young massive clusters (YMCs) similar to the massive (10^4 $M_\odot$ Arches and Quintuplet in the CMZ, and the even more massive super-star clusters (SSCs) in M82, NGC 1275, the Antennae, and similar starburst systems. The [FeII] radial velocity field of the M82 (and similar) galactic nuclear superwinds can be used to link individual sub-bubbles and outflow components to specific SSCs or recent supernova explosion sites.

2.2.5. *Globular clusters (Sobeck, Holtzman, et al.)*

Abundances in globular cluster stars are valuable to understand the nature of mixing in giant atmsopheres as well as primordial variations in abundancees that likely result from multiple generations of star formation in globulars. The H band allows the measurement of critical C, N, and O abundances.

Studies of globular cluster stars with SDSS/APOGEE are limited by the fiber collision exclusion radius. In addition, probing fainter stars in all but the nearest clusters with the 2.5m is challengin. With an IFU at the 3.5m, we could hope to provide a definitive study of abundances in northern globular clusters. The 40 arcsec field-of-view is smaller than would be ideal, but would still allow the observation of multiple stars in a single observation. A positionable fiber system would be even more compelling.

2.2.6. *Blind Emission-Line Searches of Deep Extra-Galactic fields*

A key advantage of high-resolution spectroscopy in the H-band is that the strong OH air- glow lines can be removed from the spectra, enabling deep blind searches for serendipitous emission line objects such as high-redshift Hα, Lyman-alpha, [OII], MgII], or even Lyman-α emission lines. With 10 km/s resolution such blind surveys would be sensitive to dwarf-galaxy or galactic halo emission as well as the broader emission from "normal" starburst galaxies at high to very high redshifts.

2.2.7. *ISM (York)*

There are some applications of an IFU for projects on gas that require a feed to a high resolution spectrograph R¿8000. The bundle(s) would be fed from the 2.5 meter to a 3.5m spectrograph. Two possible science cases:

1. Obtaining the highest resolution spectra possible of reflection nebulae. Two to three arcsec diameter fibers would be fine, as the main issue here is to get the best spectrum of the integrated nebula in the shortest time possible (by stacking the output of all fibers). The surface brightness of the nebulae is around 18 mag/sq. arcsec. Typical sizes are one arcminute.

   The spectrum of a reflection nebulae is the same (almost) as the spectrum of the illuminating star. In many cases, the ISM on the line of sight is BEHIND the star. The back shining light hits dust and the mirrored light comes back through the same gas, to Earth. The dust in such nebulae is typically heated, by the photoelectic effect, to 50-100 degrees K and the ISM seen in absorption in the spectrum will experience excitation from a black body radiation higher than that of most of the ISM, which is affected mainly by the CMBR at 3 degrees K

   In particular, more than one level of CN will be populated and produce absorption lines. There is a class of small molecules like CH and CH+ with upper levels not populated by the CMBR that would be excited by the thermal radiation from the reflection nebula black body. Additionally, and this is a main motivation, a candidate for the class of molecules that produce the Diffuse Interstellar Bands (DIBs) that have 5-7 atoms per molecule, would have very closely spaced rotational levels, and would produce a "band" under excitation by the CMBR. This would explain the minimum width of the unidentified DIBs that is seen for the full known set of over 600 DIBs (30-35 km/sec, as opposed to ¡1 km/sec for the three diatomic molecules mentioned above, which have very wide separations of the excited level from the ground state such that the excited lines have typical widths of interstellar absorption lines.

   Dalhstrom (Dalhstrom et al, 2013) and Oka (Oka, et al, 2013) present the case for enhancement of DIB widths in one line of sight (Herschel 36, in NGC6530) which uniquely shows excited CH+, excited CH, as well as a doubling of the widths of several DIBs (representing the population of many more rotational levels in the ground vibrational state). The star happens to have an IR star only 400AU away in projection, so a diluted IR black body is available to pump the rotational levels and explain the extra widths for the DIBs.

   Finding such an extraordinary coincidence is unlikely. Using the IR field of the reflection nebula is an alternative way to confirm the excitation that explains the anomalous DIBs, and to confirm the argument (based on molecular spectroscopy) that the DIBs are from small molecules (5-7 atoms), and idea that goes against much of the grain of the argument these days, but on weak spectroscopic and theoretical arguments.

2. A second case involves classic H II regions and extended star formation regions, also, nebular environments. Higher resolution is necessary to go beyond standard abundance analysis, to detect weak

lines needed for evaluating densities and temperatures, and to measure fluctionations over small scales in nebulae (implied by differences in T from different diagnostics). For galaxies with separated, resolved H II regions, such as M101, higher resolution is necessary to evaluate tradiditional methods of determining physical parmeters of the gas, which differs from very high to very low densities in the same galaxy: an IFU is the instrument of choice and high resolution is needed to do critical work.

2.2.8. *Galaxies (Bundy)*

Obviously, there are many spectral features however that provide chemical diagnostics of integrated stellar populations, including potential IMF-sensitive features that vary on the few percent level with IMF shape (requiring S/N 100, see (Conroy & van Dokkum 2012)). The spectral resolution required is about 6000-8000, so higher S/N could be achieved by spectral binning. The near-IR wavelengths are relatively unexplored territory for galaxy stellar population work, and APOGEE on the 2.5m provides a valuable "library" for interpreting it.

The main challenge is sensitivity, as shown in estimates below. Following up bright nearby galaxies from the ATLAS3D survey is worth further consideration however. The typical H-band surface brightness of these sources at 1 Re is about 20 mag per sq.arcsec, compared with APOGEE's target of muH = 13.4 mag per sq.arcsec (H=12.2) at a S/N 140. Stellar population modeling (without IMF sensitivity) combined with fiber stacking and longer integrations could make achieving S/N 20 feasible in annular bins, however.

Stellar Dynamics: The high spectral resolution naturally draws one to studying dynamically cold systems, where, for example, R 10,000 is sufficient for measuring out-of-plane galaxy disk velocity dispersions (5-10 km/s). This is the basis of exciting work by the DiskMass? Survey (Bershady+10) to "weigh" the mass of galactic disks. Again, surface brightness is a challenge. A fairly bright galaxy in their sample reaches 18.0 Hmag/sq.arcsec at R 10". Their CaII Triplet focused observations aimed to achieve S/N 10. But, absorption lines at APOGEE wavelengths are much weaker. However, the advantage would be the ability to potentially trace kinematically a different stellar population and, again, better penetrate the dust in the near-IR.

2.2.9. *Other (ideas from John Stocke and Jean-Michelle Desert, edited by John Bally)*

A dense-pack, hexagonal array of microlens-fed integral field unit (IFU) is ideal for precision spectrophotometry. Such an IFU can collect all the light from a star without the losses resulting from light spillover from single-fibers or slits. With a spectral resolution of R ∼ 22,000, IFU-fed APOGEE spectra can be used for precision radial velocity measurements needed for exoplanet characterization. By deploying two or more small IFUs which completely cover the full point-spread-functions (PSF) of the host star of a transiting exoplanet, and one or more reference stars, the APO 3.5 meter can be used to measure the subtle spectral changes associated occurring in and out of transit. The real-time simultaneous monitoring of target and reference stars will enable accurate correction and removal of time-variable telluric emission and absorption lines needed for precision spectrophotometry not possible with single object spectroscopy.

TABLE 2
Length Between Focus of APO Telescopes and the APOGEE Spectrograph Room

(meters)	ARC 3.5 m	NMSU 1 m	ARCSAT	SDSS 2.5 m	APOGEE
ARC 3.5 m	0	101	128	159	199
NMSU 1 m	101	0	62	94	134
ARCSAT	128	62	0	61	101
SDSS 2.5 m	159	94	61	0	40
APOGEE	199	134	101	40	0

High-precision time-domain spectrophotometrycan also be used to study low-amplitude stellar variations resulting form flares and other surface phenomena such as star spots. Low-level rotational modulation of the starlight amplitude and associated subtle variations in the shapes of photospheric lines can be used to reconstruct the surface distribution of bright and dark spots on the stellar surface. The addition of polarizers would enable surface magnetic field measurements using the Zeeman splitting of Fe and FeII absorption lines.

2.3. *Fully configurable fiber positioning projects*

Both open and globular cluster projects would benefit from a full multi-object spectroscopic (MOS) capability. A MOS capability with custom-drilled plug plates would enable precision radial velocity and abundance determination for cluster stars.

3. FIBER NETWORK

3.1. *Site infrastructure changes*

A conduit/utility tray will be installed for running fiber between the four APO telescopes using a combination of existing utility trays, new underground conduits, and new above-ground conduits or trays. When underground, the conduit will consist of two 8 inch pipes for redundancy and to allow adequate room for future fiber runs to be added. Inside the 3.5 meter enclosure, the fibers will be routed from the TR1 port through existing utility pathways through the cone and out the NE side of the pier ∼32.7 m. From the pier, the fibers will be routed a short distance, ∼4 m, in existing open cable trays before entering a new open tray at the East corner. From the corner of the pier, a new cable tray will be installed which will direct the fibers up to the ceiling of the ground level, along existing structural beams to the loading dock doors, across the top of the doors, continuing for 1 m past the doors to the East before dropping down the inside of the enclosure wall to the concert footing (∼15.8 m). The somewhat circuitous route is chosen to avoid existing underground utilities on the East side of the enclosure and to avoid trenching under the existing drive way which experiences a large amount of heavy truck traffic associated with nitrogen and equipment delivery. Figure 3 shows the proposed routing of this new cable tray as well as the existing pathway in the lower 3.5 m enclosure.

At the concrete footing for the 3.5 m enclosure, the fibers will pass through the enclosure wall and be directed run site plan.jpg

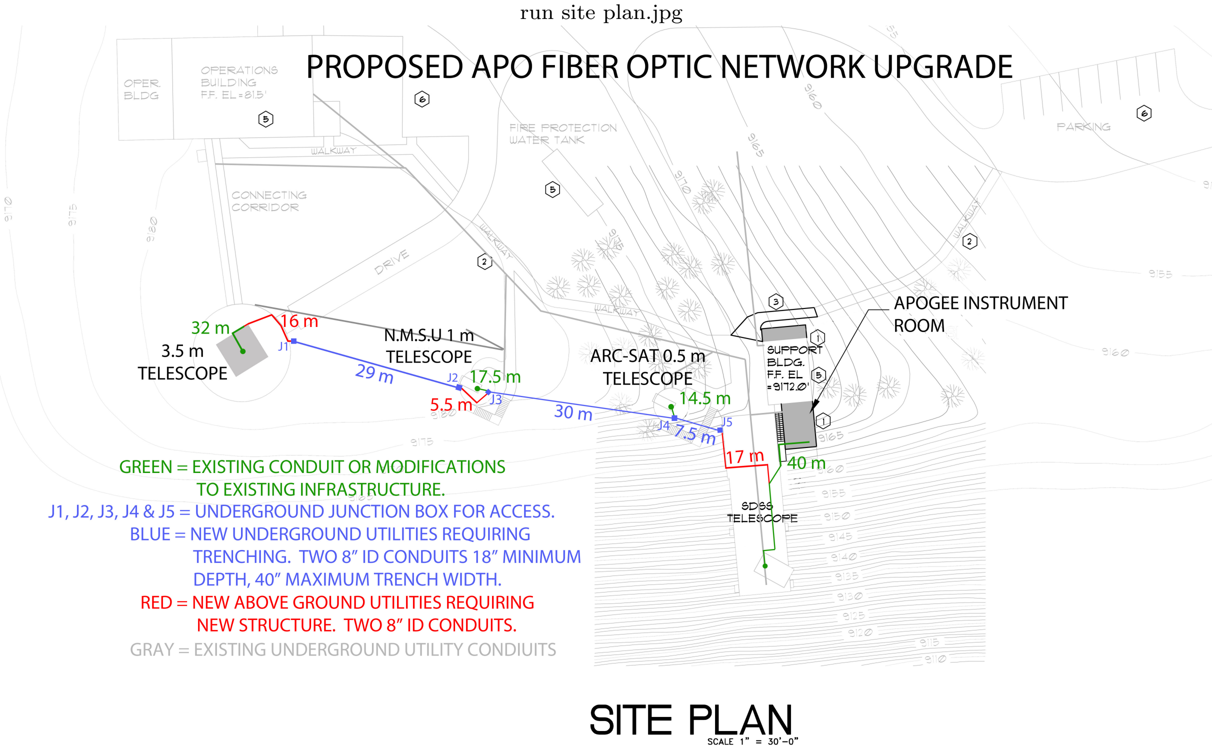

FIG. 1.— Proposed path of a new fiber optic network for Apache Point Observatory. Green lines and dimensions indicate existing cable trays or utility conduits which could be used. Red lines indicate areas where new cable trays would need to be installed. Blue lines and boxes represent new utility trenches for routing fibers underground over long runs that would require digging on site. All existing utility conduits are marked with Gray lines. The existing conduits are not addiquite due to long path lengths and small size. Many of these existing conduits have also been crushed since there installation.

FIG. 2.— The full underground run is shown in blue as seen from the observing level of the 3.5 m telescope. In order from the foreground are the NMSU 1 m, ARCSAT, and the SDSS telescope. The brown building in the far ground is the SDSS plug lab and the APOGEE spectrograph room where the existing fiber run terminates. Dashed lines indicate the fiber run is passing behind something in the image..

down into the first of five underground junction boxes. These boxes will be significantly larger than most utility access boxes to allow for easy pulling of the cables and to allow for enough room to include strain relief anchor

FIG. 3.— Image of the lower level of the 3.5 m telescope enclosure with fiber roughing marked. The green line represents existing cable trays. The red line is the proposed routing for the new cable tray. The new cable tray stays clear of both the 3.5 m primary mirror hatches and the loading dock doors. A red dot on the will at the far side of the door indicates the wall pass trough to J1. Dashed lines indicate the conduit is routed behind something in the image.

points as well as thermal expansion loops for the fibers. A commercial junction box size of 36"X36X30" will be installed such that, when closed, the lid and box will be flush with the ground level. From the first junction box (J1), two 8 inch conduits will be installed that will run ∼29.3 m South to the North corner of the NMSU 1 m pier to a second junction box (J2).

At this point, the fibers must come above ground to come around the west side of the 1 m pier where digging is complicated by the steep slope to the east and the structural footings of the 1 m dome 4. Routing around the east side of the 1 m is not possible due to existing underground utilities. The above ground section will lift the fibers 1 m off the ground into a completely enclosed tray which will wrap around the pier to the South before dropping back down to a third junction box (J3); the total above ground run around the 1 m is ∼5.5 m. At the above ground junction with J3 there will also be a short run up the side of the 1 m pier into existing cable routing which will allow access to the 1 m focus. The length from J3 to the 1 m focus is ∼17.7 m, all but 3 m of which is in existing cable access trays.

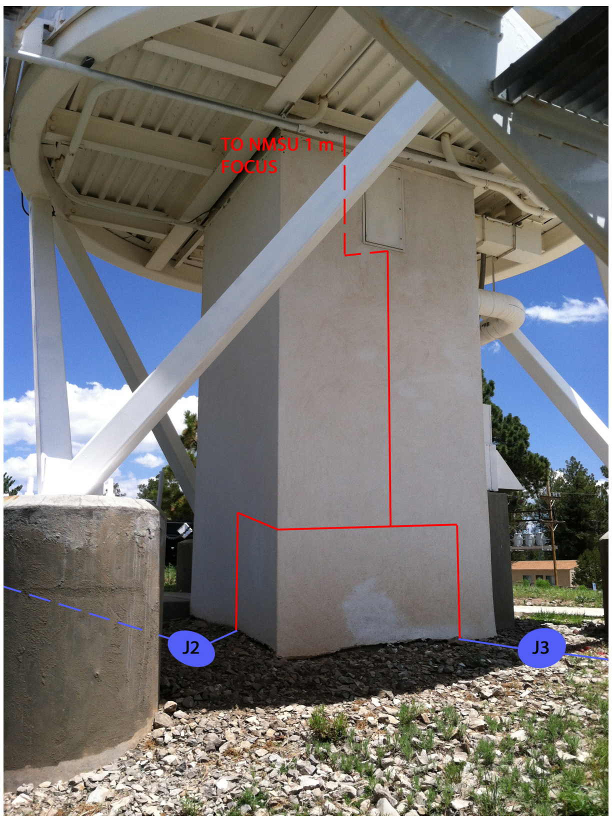

Fig. 4.— NMSU 1 m pier with fiber routing shown. Red indicates above ground section to avoid complicated digging around the 1 m base and the run up to the NMSU 1 m observing level. The blue indicates the underground run, the positions of both J2 and J3 are shown as well.

From J3 the run will continue south, again underground in two 8 inch conduits, to a fourth junction box (J4) near the SE corner of the ARCSAT pier (∼30 m). At J4 a single conduit section will be routed up the side of the ARCSAT pier and through the floor of the observing level see figure 5. Once inside the ARCSAT enclosure, existing cable routings can be used. The distance from J4 to the ARCSAT focus is ∼14.6 m, 6 m of which will require new above ground cable trays. From J4, a short underground run will continue ∼7.3 m to the SE to junction box five (J5) near the concert skirt of the SDSS 2.5 m dome track.

At the concrete skirt the existing handrail attachment structure can be used to house the new tray as it heads east to the front of the SDSS skirt. At the east end of the skirt the fiber run will again turn south underneath the dome track. The area under the dome track has existing infrastructure to support the cable run as this area also acts as the structure for all of the dome air handling equipment, and utility pathways. The new cable trays will continue to the east where it will intersect with the existing APOGEE fiber run cable tray (6). From there, the run will continue to the gang change podium of the 2.5 m telescope. In total, the run from J5 to the gang change podium is ∼40 m, of which ∼17 m will be in new cable trays.

Fig. 5.— Junction box 4 (J4) shown with the underground runs to J3 and J5 in blue. The single conduit run for the PT can be seen in red coming up the pier of J4 to the observing level of the ARCSAT telescope.

At the gang connector podium there is a fiber junction which continues on to the APOGEE spectrograph (Figure 7). This junction, called a Gang Connector, couples all 300 of the APOGEE fibers with one operation. The new fiber run terminates here as this podium will act as the switching point for changing APOGEE from 2.5 m operations to any of the remaining 3 telescopes. The fiber run in existing conduits back to the APOGEE instrument is another ∼40 m. Figure 8 shows the outside section of the existing run.

In total, the fiber network would include ∼231 m of fiber pathway, of which ∼118 m would be in existing conduits or cable trays, ∼66 m would be in new underground trenches, and ∼47 m of which would be in new above ground cable trays or conduits. Of the ∼47 m of new above ground cable trays/conduits, ∼16.5 m would be outdoors, with the remaining 30 m inside telescope

Fig. 6.— Above ground cable tray from just after J5 to the junction with the existing APOGEE fiber run tray under the 2.5 m mechanical level. The J5 box is just off the image to the left. The red line indicates the intended run of new cable tray. The red dot is the intersection with the existing APOGEE cable tray and finally the green line indicates the continuation of the existing APOGEE fiber run. Dashed lines indicated the cable tray is behind something in the image.

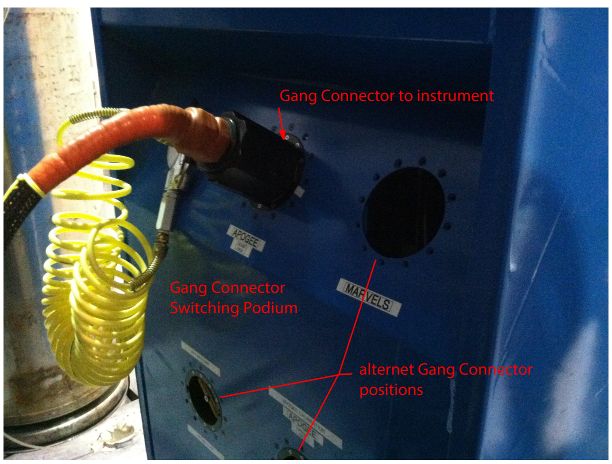

Fig. 7.— Image of the APOGEE gang connector switching podium. Each black circular cutout is an alternet position the gang connector can be placed in to direct light from different calibration system or the 2.5 m telescope. The position marked MARVELS would contain the junction point for the small aperture and the 3.5 m fiber feed.

enclosures.

3.2. *Fiber Optic Performance*

A key component of the performance of a fiber optic system for astronomy is the throughput of the fiber system, which is normally given as a percentage of the light delivered to the instrument through the fibers.

$$Throughput = Fiber_{output}/Fiber_{input}$$

Contributing factors to losses within a fiber system are Fresnel losses (section 3.2.1) at the ends of the fiber, attenuation within the fiber (section 3.2.3), and focal ratio degradation (FRD). Both Fresnel losses and fiber attenuation are well understood. Fresnel losses can be directly calculated, while fiber attenuation is normally provided via a wavelength dependent curve measured during the fiber production and provided by the fiber vendor. FRD is somewhat more difficult to quantify as it encompasses a number of contributors which act to scatter light to faster than expected f-ratios. From experience with other fiber systems, an upper bound can be placed on the effect FRD can have. Lab tests performed on MaNGA fibers showed that only about ∼6% of the light was scattered to speeds faster than f/4 when extreme stresses were induced in the fibers. In this case the input f-ratio was f/5. Other contributors to FRD can include the quality of the surface polish and plane of polish at the ends of the fiber. The existing APOGEE fiber run between the SDSS telescope and the instrument is ∼40 m, while the new run to the 3.5 m would be ∼200 m. For the purposes of this proposal, we will assume the FRD of the 200 m run will be roughly equivalent to the existing 40 m run. Instrument performance on the 3.5 m can then be put in context of performance demonstrated on the SDSS telescope.

Fig. 8.— Image of the existing APOGEE fiber run tray marked in green from where it exits the APOGEE instrument room the junction with the new run (Red) and the path to the 2.5 m telescope. Dashed lines indicate where the cable tray passes behind something in the image.

3.2.1. *Fresnel Losses*

Fresnel losses at each air-glass interchange can account for up to a 3.5% loss in total throughput. Recent work into AR coatings on assembled fiber faces conducted by the MaNGA project has led to coatings which can almost eliminate Fresnel losses a the fiber faces(Drory et. al, 2014). In lab and on-telescope tests of the 2 m long MaNGA harnesses have shown that a 5% gain in throughput can be made to the total system performance by the addition of the AR coating (Figure 9). This is for a fiber assembly with 2 air-glass interchanges, effectively reducing the losses at each air-glass interchange to 1%. APOGEE operates at a slightly longer wavelength than the MaNGA fibers, but it is believed that the process for AR coating finished assemblies can be adapted to the near-IR with similar results. For the fiber run between the three telescopes the addition of AR coatings should improve total instrument throughput by ∼8% over the performance of the SDSS fiber run.

3.2.2. *Gang Connector Coupling Losses*

A key technology needed for implementation of a fiber network at APO is the *gang connector* which is capable of coupling the 300 APOGEE fibers with a single connection (Figure 10). Inside of this gang connector are

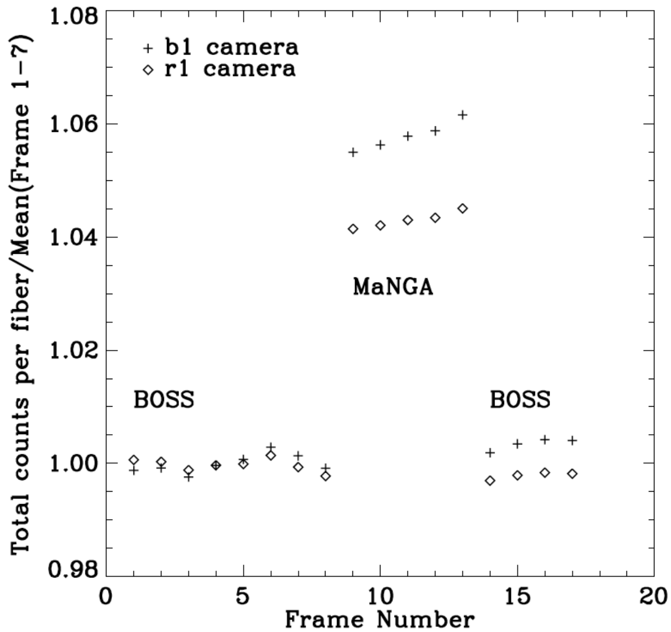

FIG. 9.— Comparison of the mean per fiber throughput between BOSS (W/O AR coating) single fibers and MaNGA (W/ AR-Coating) IFUs. As expected fro the AR coating curve the MaNGA fibers preform about 4% better than the uncoated BOSS fibers. This shows a reduction in fresnel losses of about 1.5% for each air-glass interchange.

10 custom MTP connectors built by US Conec of Hickory, NC. Each MTP connector consists of a glass filled polyphenylene sulfide ferrule with 30 fiber locating holes and a spring loaded floating mount system. As built, the precision of these ferrules is incredibly high. Each fiber position can be controlled to within 3μm. The individual ferrules mate to each other with a set of indexing pins on one side and a matching set of holes on the receiving side. The floating nature of the connector allows the ferrules to align its mating ferrule as the connection is made. When mated, the ferrules press against their mating connector with 20 N force generated by a preload spring in the connector. The self aligning feature and spring loaded connection yields exceptional coupling efficiency. When these MTP connectors are packaged into the gang connector assembly the 300 fiber connection can be made in seconds. Coupling losses in the optical have been measured through this system in the lab and only generate a 5% decrease in overall throughput at each connector junction (Wilson et. al, in prep).

This is better than the predicted fresnel losses of ~7%. With index matching coupling gel and AR coatings, these losses could be taken to nearly zero.

3.2.3. *IR Attenuation*

Fiber attenuation in the near-IR has a far lower effect on total system performance than it does in the optical. For the most part the APOGEE pass band has less than 2 db/km attenuation. For the long 200 m run between the 3.5 m and the APOGEE spectrograph this equates to only a 9% loss in the fibers for the majority of the APOGEE wavelength coverage. The existing 40 m run between the APOGEE spectrograph and the SDSS focal plane experiences a ~2% loss. The expected decrease in instrument efficiency for a fiber run to the 3.5 m is

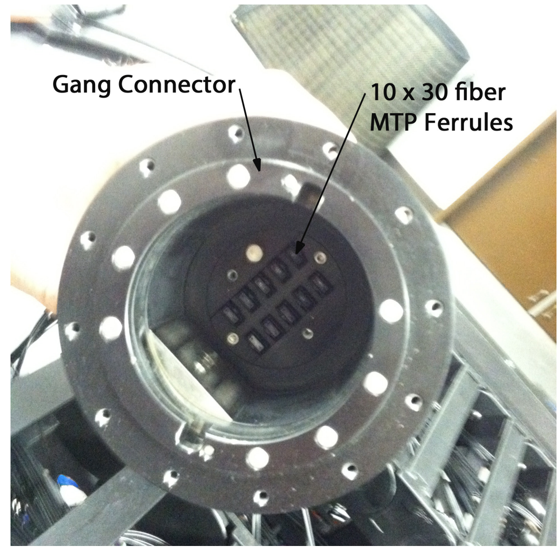

FIG. 10.— Receiving end of the APOGEE gang connector. A bayonet style connector slides into the bore and locks with a quarter turn. Ten 30 fiber MTP ferrules cab be seen in an array inside the connector body.

then a manageable ~7%. The expected losses to the small aperture telescopes are even smaller at ~2% for the run to ARCSAT and ~4% for the run to the NMSU 1 m. Figure 11 shows the expected percent losses due to attenuation from 1.5μm to 1.7μm.

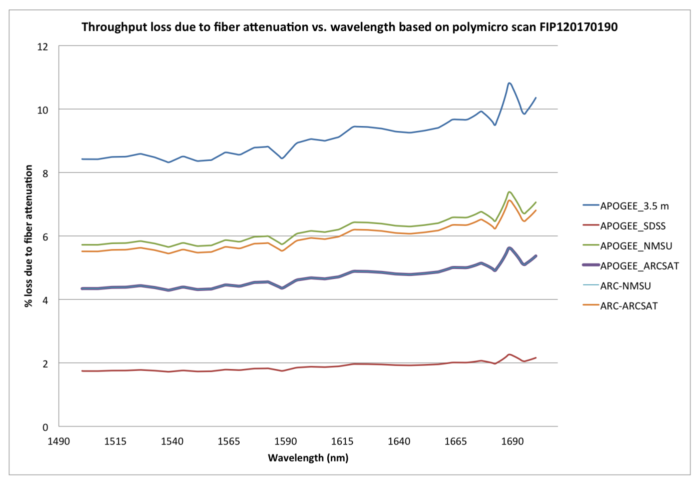

FIG. 11.— Expected percent throughput losses for fiber runs between the APOGEE spectrograph and the 4 telescopes on site as well as between the 3.4 m telescope and the two small aperture telescopes from λ = 1500 - 1700 nm. Values are based on an attenuation scan supplied by Polymicro.

3.2.4. *Total Attenuation*

With these contributing losses, the predicted worst case system loss in the fiber optic run alone is between ~22 - 25% for the long run to the 3.5 m, ~20 - 22% to the NMSU 1 m, and ~19 - 20% to ARCSAT. It should be noted that the predicted losses for the existing run from the APOGEE spectrograph to the focal plane of the SDSS telescope is between ~18.5 - 20%. The gains produced in the AR coating almost completely balance out the losses from fiber attenuation. Coupling gels inside the gang connector and careful attention to FRD may lower the fiber system losses even further.

3.2.5. *Optical Attenuation*

As optical wavelength fiber runs may be considered in the future between DIS and the small aperture telescopes; or BOSS and the 3.5 m telescope attenuation with in these runs should be considered In the exiting BOSS fiber run between the SDSS focal plane and the BOSS spectrographs mounted on the bottom of the mirror cell the fiber length is only 2 m. At this length fiber attenuation can be neglected as less than 2% even at short wavelengths down to 300 nm. For longer lengths the fiber attenuation can become the dominant source of losses. Figure 12 shows the optical attenuation which could be expected between the different focal planes of the site.

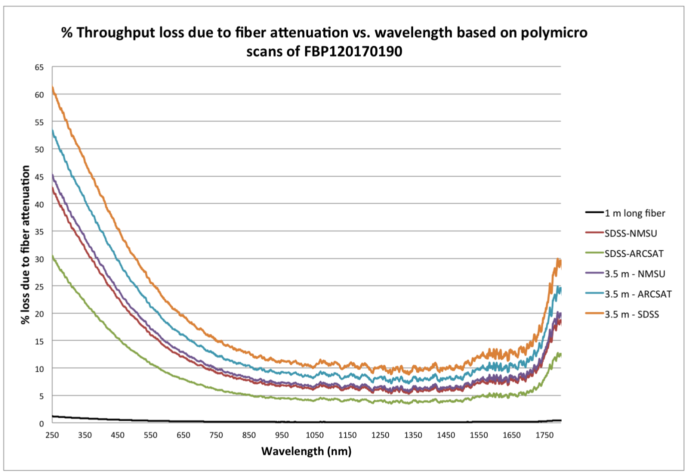

FIG. 12.— Expected percent throughput losses for fiber runs between the 4 telescopes at APO in the optical from λ = 250 - 1700 nm. Values are based on a attenuation scan on fibers used for the BOSS spectrograph.

As can be seen ilosses due to attenuation are worst at shorter wavelengths for longer runs (figure **??**. This would need to be taken into account when evaluating the effectiveness of long fiber runs, particularly to the small aperture telescopes.

A n attractive future option for optical fiber fed units might be a fiber feed between the DIS spectrograph and the 3.5 m focal plane as the fiber lengths could be kept to a minimum ($\sim$4 m). Future bench mounted spectrographs in the basement of the 3.5 m would also be worth considering.

4. APOGEE FIBER LINK

The APOGEE spectrograph is a near-infrared $\lambda = 1.51$ - 1.70μm, fiber-fed, multi-object (300 fibers), high resolving power ($R \sim 22,500$). For all of bright time and roughly 1/2 of dark time, this instrument is used in campaign mode as a component of the SDSS-IV surveys. This leaves between 21 and 45 nights per quarter that this instrument sits idle. The proposed fiber feed project is intended to broaden the use of this spectrograph by allowing users of the ARC 3.5 m telescope to access the APOGEE spectrograph during the unallocated time. 270 of the 300 available fibers will be routed 200 m from the TR1 port of the 3.5 m telescope to the APOGEE spectrograph. 40 m of this fiber run already exists as the link between the 2.5 m telescope and the APOGEE instrument. The remaining 30 fibers will be split into two groups of 15 fibers routed to the two smaller aperture telescopes on site. During 3.5 m, 1 m, or ARCSAT operations the fast swap gang connector will be moved from the connection to the 2.5 m to the port for the alternate telescopes.

4.1. *3.5 m Fiber Feed*

The fiber link between the 3.5 m telescope and the APOGEE spectrograph will consist of a 200 m fiber run, 40 m of which is achieved using the existing APOGEE fiber link. The remaining 160 m will require new fiber. The new fiber run will start at the gang connector podium and will follow the path laid out in section 3, finally terminating a few meters from the 3.5 m TR1 focus at another gang connector. Each gang connector which contains 9 groups of 30 fibers terminated into costume MTP connectors for a total of 270 active fibers delivered to the focal plane of the 3.5 m. Fibers within the long run will be jacketed in groups of 30 which will then be bundled together into a crush proof jacketing rated for outdoor use. Two *spare* sets of 30 fibers will also be included in the run and terminated into loose 30 fiber MTP ferrules. These two sets of fibers can be swapped into the gang connector should there be a failure of an MTP ferrule on ether end of the run. In total, the fiber run between APOGEE and the 3.5 m focal plane will contain $\sim$53 km of new fiber.

While the fiber run to the 3.5 m can conceivably be routed to any of the 7 instrument ports, the TR1 port, a Naysmyth port at the rear of the telescope, will be used, see figure 13. This port is currently unoccupied and can be configured with both rotator and guider to become the 3.5 m fiber feed port. Utilizing this port has the added advantage of staying away from the crowded NA2 side of the telescope where the bulk of the 3.5 m instruments are located. The TR1 port is accessed by rotating the tertiary mirror to direct the beam to the port. This change can be made in a matter of minutes due to the actuation of the tertiary mirror of this telescope.

A short run of fiber will then be connected via the 3.5 m fiber gang connector to the corrected focal plane of the TR1 port. While making a break in the fiber run at the 3.5 m is not absolutely necessary, it adds in the ability to change out the final focal plane configuration of fibers while only replacing a short run of fibers. This also allows for easy replacement of damaged fibers at the focal plan where motion due to the instrument rotator is more likely to damage the fibers.

4.1.1. *Guiding and Field Rotator*

A new rotator and guider system will also be installed on the currently empty TR1 port. The rotation and guiding system will need to be flexible enough to accept other fiber-fed applications in the future so more capacity in the rotator and a larger clear aperture than necessary for the APOGEE fiber run will be included in the rotator. The telescope f/10 design in combination with the existing tertiary baffling does not lend the 3.5 m telescope to '*wide*' fields of view a the Nasmyth ports. The existing tertiary baffles begins to vignette at a field diameter of $\sim 9.5'$, effectively limiting the field of view for science

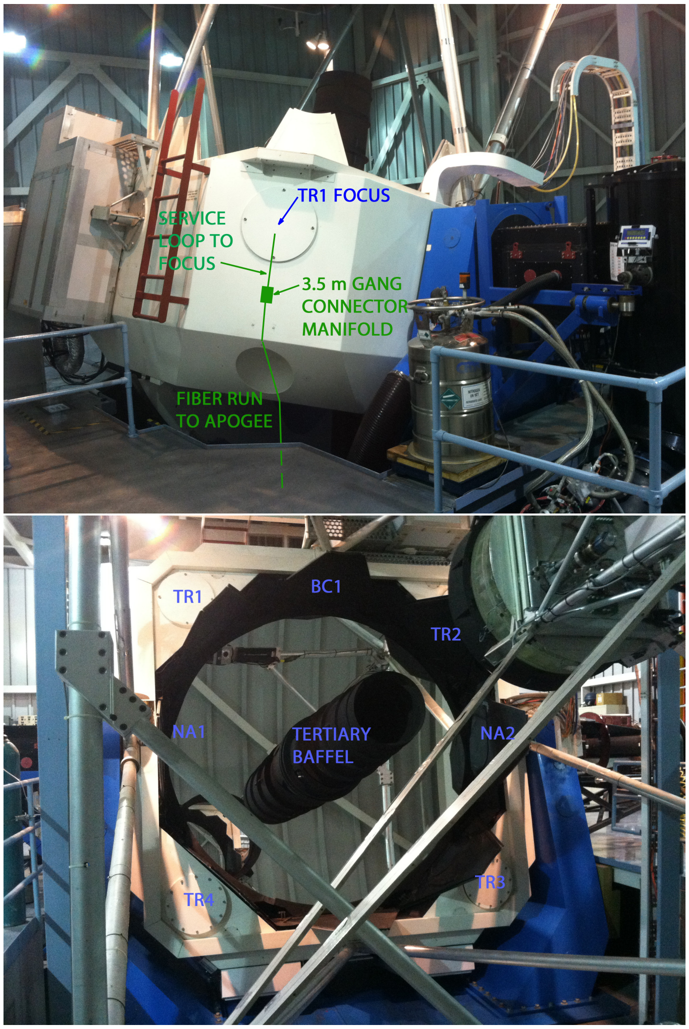

Fig. 13.— Top: The currently un-used TR1 port of the 3.5 m telescope. The native focus of this port is 24.25 inches back from the flange shown with the blue arrow. The focal reduces needed to produce the f/5 beam will bring the focus to ∼12.95 - 11.7 inches in relation to the flange shown. The gang connector junction is show attached to the side of the primary mirror support system in green, the green lines represent the fib run. Bottom: All 7 of the 3.5 m ports as seen from behind the secondary mirror. Each port can be accessed by rotating the robotic tertiary mirror hidden inside the black baffle at the center of the primary mirror. A tertiary mirror rotation takes less than 2 minutes

applications to $\sim 9.5'$. In addition to the tertiary baffle vignetting, the focal plane is noticeably curved at an average field curvature of 1389.11 mm. This corresponds to a broadening of the RMS spot size from $\sim 6.59\mu$m on axis to $\sim 7.85\mu$ at a field radius of $2.4'$, which further complicates the design at larger field sizes.

The proposed TR1 port will allow for a $\sim 9.5'$ diameter clear aperture through the rotator to take advantage of the full un-vignetted field. Guiding will be accomplished by a 8 degree tilted fold mirror near focus. This fold mirror will have a $\sim 40''$ ($\sim$3.8 mm) hole in the center to allow light to travel to the IFU which will be built into the fold mirror itself. In this way the fold mirror will act in the same way as a traditional slit viewer. Science targets can be acquired on the fold mirror and then offset on to the center of the IFU.

4.1.2. *IFU Design*

Research into integral field unit (IFU) design for the MaNGA project has led to the development of a novel way to build large scale, inexpensive, and highly ordered fiber IFUs (Drory et al. 2015). This has been enabled by the development of in-house manufacturing process development and precise metrology techniques now available at U. Washington and U. Wisconsin. Figure 14 shows images of all 6 different IFUs build for the MaNGA survey. By adapting these techniques to the production of large scale monolithic fiber bundles we can further capitalize on the large engineering investment of the MaNGA project.

Ongoing research has lead to bare fiber IFUs with up to 547 (figure 15) fibers accurately placed to within 4μm RMS of the ideal fiber position, with 90% achieving a better than 6μm placement. The accuracy to which the 547 fiber IFU has been built is at the same level which is typically seen in the production IFUs used for the MaNGA project that contain between 7 and 127 fibers. While the APOGEE fiber feed to the 3.5 m would only incorporate a 217 element IFU, the work done to demonstrate the techniques used for the MaNGA IFUs scales to IFUs of larger sizes give us confidence in our ability to built a 217 element IFU of high regularity in the fiber positional placement as well as excellent optical properties.

While the APOGEE spectrograph does accept 300 individual fibers there are a few aspects of the fiber system design that limit the number of fibers available to the 3.5 m. First, the design of the gang connector discretizes the fibers into ten 30 fiber groups, as this is the number in a single costume MTP ferrule designed for SDSS by US Connec. As we want to feed APOGEE with all three telescopes, it follows that we should dedicate one of the ten groups of 30 to the two smaller telescopes. This way if a failure were to occur in the small aperture run the larger 3.5 m run would not need to be replaced to fix the break in the small aperture run. This leaves 270 fibers available to the 3.5 m. The hexagonal packing of the IFU discretizes the number of possible fiber within the IFU. For coupling to the 270 available fibers of the APOGEE spectrograph, a 217 fiber science IFU is likely an optimal number of fibers for achieving the largest possible size while still allowing for an adequate number of fibers (49) for sky subtraction.

An additional benefit afforded by the highly controlled regularity of fiber position generated by this IFU technology will allow for the efficient use of micro-lens arrays at the entrance of both the science IFU. This will enable truly integral field observations over a full $\sim 39''$ field of view (FOV). This micro-lens array coupling would be built to reproduce the APOGEE spectrograph expected f/5 input and would underfill the fibers slightly to compensate for the small errors in the fiber positions, and micro-lens manufacturing. Lithograph manufacturing processes have allowed for far more complicated micro-optic arrays at far cheaper prices than have been available in the past. This technology also allows for highly customized array patters. It is, however, likely that the high accuracy of fiber placement alone will allow for use of *'off the shelf'* micro-optics, further reducing price. Micro-lens arrays using these types of lithograph etched lenses have been uses with good sucsess on the LRS2 in-

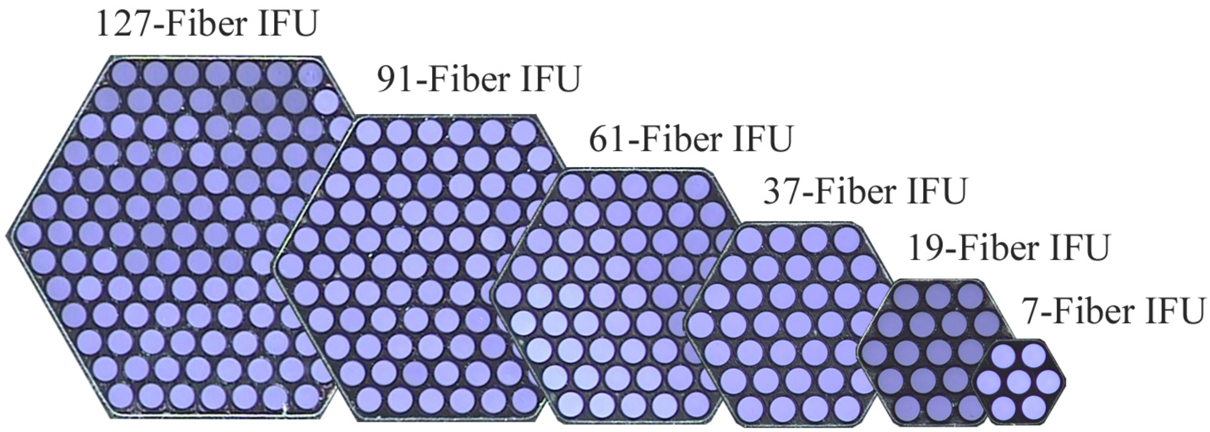

FIG. 14.— Images of the production MaNGA IFUs with the fiber count listed next to each size. Roughly 200 total IFUs of versus sizes were built for the MaNGA survey.

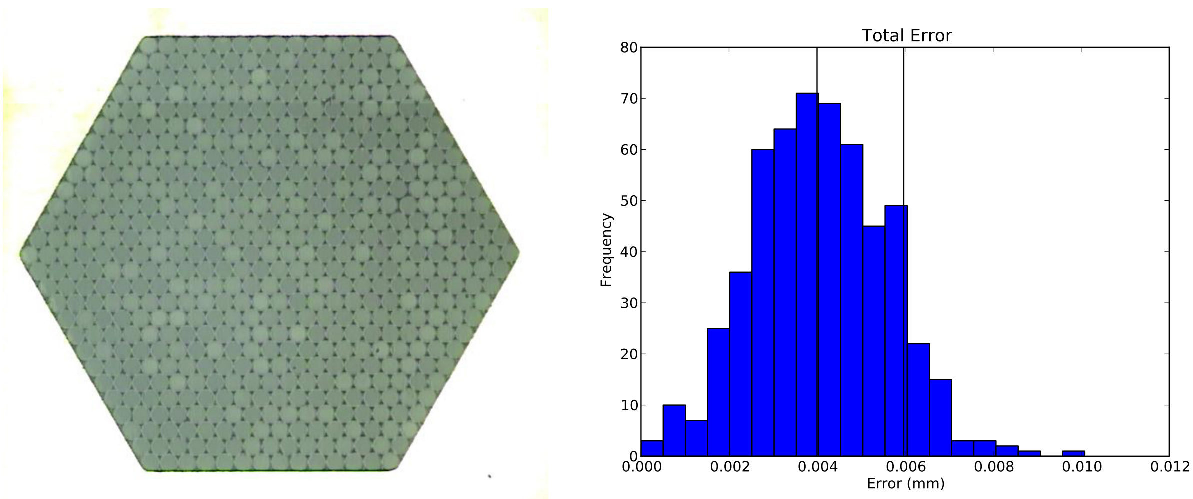

FIG. 15.— Left: 547 fiber IFU terminated into a tapered hexagonal stainless steel ferrule. Right: Distribution of fiber deviation from perfect placement within the IFU, vertical lines indicate the media error (4 μm) and the 90% threshold error (6 μm)

strument (Chonis, T. S., et al. 2014) A simmilar design is being considered for the APOGEE IFU. This micro-lens array will map the expected 190 μm fiber pitch to the 120 μm fiber core size while maintaining the 1.4$''$ spaxel size. A focal reducer would be used to speed up the native f/10 input beam to ~f/5.5 before final correction at the micro-lens array to the expected f/5 input. The relatively small FOV will help to control complexity and size of the needed focal reducer. It is worth mentioning that in both lab tests and on sky measurements the focal ratio degradation (FRD) seen within the fiber bundles used on the MaNGA survey are the same as found with the corresponding single fiber assemblies used on the same instrument. This gives us confidence that by preserving the input f-ratio on the same fiber used for APOGEE will not lead to beam mismatch at the spectrograph input. Spectrophotometric precision within bundles is also high at between ~3 - 5%.

Of the remaining 53 fibers, 49 will be distributed into seven small mini-bundles each containing 7 fibers. These mini-bundles will be placed in a fixed radial pattern around the central IFU for use as sky subtraction fibers. While fixed locations of the sky fibers can lead to the possibility of contamination by bright objects within the field, the fixed location greatly reduces the cost and complexity of positioning systems. The six sky subtraction mini-bundles will be distributed in a 8$'$ diameter ring around the central IFU every 45 degrees, with one missing position needed for the tilted guider optics. The sky fibers will be interleaved with the IFU fibers at the 3.5 m observing level gang connector in such a way as to distribute the sky fibers along the slit as evenly as possible.

It is worth noting that the central IFU can also be used for point source observations. By offsetting a science target onto the IFU and looking at the differential flux in the fibers the target center can be determined so that the position can be fine-tuned to center the target on a single fiber within the bundle (Yan et al, in prep). This will allow users to deal with only a single fiber spectrum if they wish rather than the more complicated data produced when viewing extended objects. Sky subtraction for point source targets can then be done using the outer ring of mini-bundles or IFU fibers without target light flux. Finally, 4 fibers will remain unused.

4.1.3. *3.5 m fiber link performance*

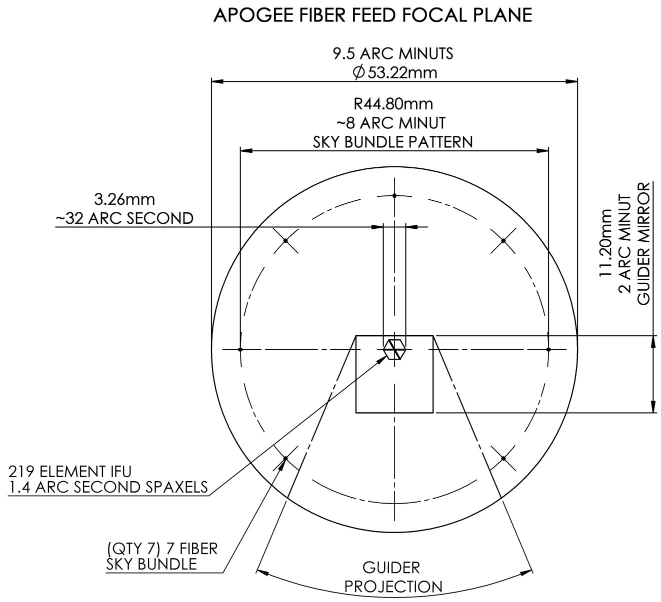

FIG. 16.— Schematic view of the 3.5 m fiber feed focal plane with the central 217 fiber IFU, and 7 sky subtraction bundles. All bundles are shown to scale within the 9.5′ field of view. The central IFU is coupled to a micro-lens array to provide full spacial coverage over the 0.65′ field, Each fiber images an area ∼1.4″ across. The square ∼2′ FOV guider flat is shown as the square in the plane view, the guider mirror is at a slight angle to the incoming beam and projects the guider field down to a second fold mirror and then back past the focal plane to a guide camera.

Performance of the APOGEE fiber run is expected to be quite high. The addition of the AR coating to all of the fiber interfaces is expected to produce a net gain of ∼5%. This is tempered somewhat by the added attenuation losses for the 200 m run of 9%, although with the addition of index matching gel at the 3.5 m gang connector it is possible the 3.5 m run will have better inherent instrument throughput than the existing SDSS fiber run. The smaller 1.4″ spaxel size accounts for nearly a 40% improvement on spacial resolution over the fibers on the 2.5 m. The adaptation of micro-optics for true integral field coverage improve the overall IFU fill factor from ∼56% to nearly 100%, nearly doubling the collecting area and producing a factor of 1.3 improvement in signal to noise.

4.2. *NMSU 1 m link*

The NMSU 1 m has an existing fiber run to the APOGEE instrument that has been used as a technology demonstrator of the fiber optic network at APO. It currently contains 10 fibers which run through 200 m of existing conduit. The run also contains three more fiber joints than needed as it was build using test assembles left over from the APOGEE development. It is not at all optimized for run length, coupling losses, or FRD induced in the fiber due to tight bends in the conduit and collapsed sections of conduit near the 1 m. The existing fiber feed is integrated into the guider fold mirror of the NMSU photometer and is currently used for a bright star survey to complement the existing APOGEE survey. The comparable f-ratio of the 1 m, f/6, as compared to the f/5 of the 2.5 m allows for a fiber run without the need for f-ratio correcting optics. The design of an existing photometer guider with a fold mirror at focus also provides a readily available mounting point for the APOGEE fiber feed. For use with the photometer there is a 20″ hole at the center of the flat which allows light to pass trough to the photometer. The original flat has been replaced to also include 10 embedded fibers along the horizontal (in focus) axis of the mirror. The fibers are inline with the incoming beam of the telescope and at focus on the fiber tip. This configuration allows us to use the photometer guider to place bright targets on one of the 10 fibers. The remaining 9 fibers are used for sky subtraction.

Unfortunately, the throughput performance of this existing feed has been worse than might have been expected, by over a factor of two. It is unclear what is responsible for this, but note that the current fiber run is sub-optimal, with several sharp turns in the fiber. It is possible that this is introducing more severe FRD than expected, which could cause significant throughput loss.

By introducing a new set of fibers in the improved trench, and with only two fiber couplings; one at the gang podium and one 2 m back from the focal surface, we expect to reduce this drop significantly at a very low cost of the 134 m of fiber.

Because of the close match between the f-ratios of the SDSS telescope and the NMSU 1 m there is no need for focal reduction optics, which simplifies the design considerably. In both the SDSS telescope and the NMSU 1 m the fiber size is significantly larger than the FWHM average seeing so the fibers are under filled when observing point source targets. The median seeing on the SDSS telescope is ∼1.1″ which is delivered to a 2″ fiber. On the NMSU 1 m the median seeing is ∼ 2″. The simple area ratios of the telescope apertures and the fiber losses are the only contributing factors.

4.3. *ARCSAT link*

The Astrophysics Research Consortium Small Aperture Telescope (ARCSAT) is currently available for subscription by ARC users. The available instruments include two imagers FlareCAM a blue optimized Apogee U-47UV Alta 1024X 1024 camera with 13 μm pixels and a 10 filter changer, and Survey Cam an Apogee UIbM-HC Alta 4096x4096 with 9 μm pixels.

While developing a full APOGEE fiber-feed from the ARCSAT telescope is not included as part of this project, the fibers will be ran into the dome. A future project to add in a guider and focal reducer can be considered to feed APOGEE from ARCSAT. Assuming any future application would reproduce the expected f/5 focal ratio for the APOGEE spectrograph the fiber size on sky would be ∼9.8″.

5. BUDGET

The total estimated hardware budget for the infrastructure improvements and the APOGEE fiber feed completed to the 3.5 m telescope and the NMSU 1 m is \$363.3k. Almost \$150k of this is needed to complete infrastructure improvements to the site and for running the long fiber run between the existing run and the observing level of the 3.5 m telescope. ∼\$92k is then required for needed infrastructure improvement to the 3.5 m telescope including the addition of an instrument rotator,

TABLE 3
PROJECT BUDGET NOT INCLUDING LABOR

Item	Cost (kUSD)
Infrastructure Improvements	
Underground Trench and Conduit	19
New Above Ground Conduit	9
Fiber Run	
Raw Fiber FIP120170190	80.5
Assembly charges 3.5 m run	30
Assembly charges ARCSAT and 1 m run	4
MTP ferrules and Gang Connector	6.8
Instrument Rotator	
Rotator Hardware	18.6
Rotator Electronics and MCP	7
Guide Camera	
Fold Mirrors	0.2
Structural suport	8
Apogee F47 Camera	30
Focal Reducer	
f/5 Focal Reducing Optics	18
Lens Cells	5
Instrument Baffling	5
IFU Assembly	
Micro-lens Array at IFU	20
Micro-lens Alignment Tooling	20
Raw Fiber FIP12170190	2.3
Fiber Assembly at C-Tech	30
MTP and Gang Connector	3.5
IFU Ferrule development	10
IFU Ferrule production	2.5
Sky Fiber Ferrule	3.9
Instrument Structure	10
Manufacturing Tooling	10
TOTAL	**363.3**

focal reduction optics, and guide cameras. The remaining ∼$112k is then needed for the development of the 3.5 m IFU. Table 3 gives the estimates of the total hardware costs for major line items within the budget. Where possible quotes have been used to generate these numbers. For more complicated items such as the rotator, past project cost of similar complexity has been used to generate these values.

Labor requirements are not included in the project budget. This is primarily because much of the labor required to preform the work needed is already an overhead cost to the observatory or can be found through in-kind contributions of institutions who may wish to join ARC outright or gain access to the 3.5 m through the leasing program. Some labor may need to be paid for by ARC, for work performed at other institutions; but the bulk of the labor will come from existing staff. A preliminary estimate of personnel resources as well as the duration and level of there commitment is included in table 4.

The expected duration to completion is just over 2 years from the time the project is approved. Over that two years, roughly 40 person months of labor will be required split over a number of people from different disciplines.

A project manager will be required at a low time commitment for the duration of the project to manage the schedule and budget, as well as vendor contracts. This person will also be responsible for coordinating groups working on different aspects of the project.

Mechanical engineering is also needed for the duration of the project for the design/implementation of site infrastructure improvements, 3.5 m telescope upgrades, IFU design and validation, and commissioning. This position could be managed by one person or could be split between two to give more work to an institution looking for in-kind credit.

TABLE 4
PROJECTED LABOR REQUIRMENTS

Labor Skil Set	Person Months	Commitment Level (% full time)	Duration (Months)
Project Management	5.5	20%	27.5
Mechanical Engineer	13.75	50%	27.5
Optical Engineer	4.5	75%	6
Software Engineer	7.5	50%	15
Electrical Technician	1.25	75%	1.6
Astronomer	7.75	50%	15.5

Optical engineering will be required for short durations at three times during the project. Early in the project for design of the focal reducing optics and micro lens geometry. Near the middle for development of metrology methods for aligning the micro lens array. Finally late in the project for design validation and testing both in the lab and on the telescope. Optical engineering could likely be split between U. Wisconsin where the SDSS testing equipment was manufactured, UVa who have intimate knowledge of the APOGEE spectrograph, and U. Texas who are currently the most capable group for designing micro lens array coupled systems.

Software engineering will be required at many levels. At the lowest level, motion control software will need to be developed for the instrument rotator and any other potential robotics needed in the system. Guider control software will also need to be developed. At a slightly higher level, the Instrument control (ICC) will need to be developed. At the highest level, the instrument will need to be integrated into TUI. There will also need to be a software effort at U. Wisconsin to adapt the SDSS test stand to be used for micro lens alignment and IFU metrology.

Parallel to the functional software work, data reduction tools will need to be written so that astronomers can easily extract either RSS or data cubes from the raw IFU data. A module will also need to be developed for stellar astronomers to extract single object spectra. Much of this interface can likely be copied from the MaNGA data reduction pipe line used for BOSS data and the existing APOGEE DRP used for the APOGEE survey. This position will require an astronomer or graduate student knowledgeable in using IFU data.

Lastly, an electrical technician will be required during installation of the instrument rotator and guiding system to build cables, any needed brake out boards, and for trouble shooting of the system during installation. This person will also be needed at a low level during development to help inform designs decisions regarding all robotic components.

6. CONCLUSION

We have presented a proposal to develop the infrastructure for fiber links between the telescopes at Apache

Point Observatory, and to fully implement fiber feeds from the ARC 3.5m and the NMSU 1m to the SDSS APOGEE spectrograph. Such a capability takes advantage of the significant investment made for the APOGEE spectrograph, allowing it to be used essentially 100% of the time. The addition of the fiber conduite to the site and the adaptation of hte TR1 port of hte 3.5 m telescope for fiber use will lay the gound work for many future instrumentation projects.

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