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THE NARROW-FIELD TELESCOPE SCIENCE CASE: A PROPOSAL

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RESUMEN

Basado en las capacidades observacionales que supuestamente estarán disponibles desde tierra y el espacio alrededor de 2015-2020, así como los intereses tradicionales de la comunidad astronómica mexicana, propongo que el telescopio de campo angosto (NFT) esté dedicado a la espectroscopía de alta resolución, cubriendo el intervalo espectral que va desde el óptico hasta el infrarrojo medio, y a la imagen directa y espectroscopía (de mediana a alta resolución) con óptica adaptativa en el infrarrojo cercano. Estas capacidades permitirán el estudio de los procesos responsables de la evolución galáctica después de la época de la acumulación de la masa: el desarrollo de la estructura galáctica, la formación y estructura estelar, la distribución de masas estelares, la cinemática y composición química de las estrellas y del medio interestelar.

ABSTRACT

Based upon the capabilities that are likely to be available from space and terrestrial observatories around 2015-2020 and the traditional interests of the Mexican astronomical community, I propose that the narrow-field telescope (NFT) be dedicated to high resolution spectroscopy covering wavelengths from the optical to the mid-infrared and adaptive optics imaging and spectroscopy (medium to high spectral resolution) in the near-infrared. These capabilities would permit studying the processes responsible for galaxy evolution after the epoch of mass assembly: the development of galactic structure, star formation, stellar structure and mass distributions, the kinematics and chemical composition of stars and the interstellar medium (ISM).

Key Words: **GALAXIES: GENERAL — INSTRUMENTATION: SPECTROGRAPHS — ISM: GENERAL — STARS: GENERAL**

1. INTRODUCTION

Allegedly, while discussing the proposed construction of the 200-inch telescope at Palomar with George Ellery Hale, a member of the Rockefeller Foundation's Board inquired of Hale "What discoveries will you make?" Hale reputedly replied "If we knew what the discoveries were likely to be, it would make no sense to build such a telescope". (on-line LSST documentation)[2].

Whether myth or fact, the foregoing illustrates the intrinsically speculative nature of the present exercise. What follows is based upon interpolation and extrapolation of our current understanding of astronomical phenomena and is not particularly endowed with insight or intuition. Hopefully, the most important discoveries that await are not even described here! I focus upon the areas of astrophysics where the NFT could or should be competitive without dedicating much effort to detailed instrumental specifications, though working instruments are taken as guides as to what is feasible.

Table 1 presents some of the projects that will be completed within the next five years and in the decade following 2010. The current generation of projects will be complete, or have ended in the case of some space-based facilities, within the coming five years. The subsequent generation of instruments will be brought into operation during the decade following 2010. These instruments will have a profound impact upon our understanding of astrophysics: the GAIA satellite will allow an unprecedented study of the structure and evolution of the Milky Way and the Magellanic Clouds, the Large Synoptic Survey Telescope (LSST) will open up the large scale study of temporal variability over an entire hemisphere of the sky, the James Webb Space Telescope (JWST) should detect the first light objects in the universe, the Large Millimeter Telescope (LMT/GTM) may detect large populations of high redshift galaxies, the Atacama Large Millimeter Array (ALMA) and the Square Kilometer Array (SKA) will take radio astronomy into new realms, and a variety of space missions should revolutionize our understanding of planet formation.

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[2]See http://www.lsst.org/Tour/concept.shtml

TABLE 1

OUTLOOK: OTHER FACILITIES

In the next 5 years:	The decade following 2010:
• 8- and 10-m class telescopes will be completed	• GAIA mission planned for launch 2011
• Large Millimeter Telescope (LMT/GTM) will be completed	• Atacama Large Millimeter Array (ALMA) expected to be complete 2012
• COROT satellite planned for launch 2006	• Large Synoptic Survey Telescope (LSST) first light planned for 2012
• World Space Observatory (WSO) planned for launch 2007	• James Webb Space Telescope (JWST) planned for launch after 2013
• Herschel mission planned for launch 2007, ends approx. 2011	• Terrestrial Planet Finder planned for launch 2014-2020
• Spitzer mission terminates approx. 2008	• Square Kilometer Array (SKA) expected to be complete 2014, in full operation by 2020
• Kepler space mission planned for launch 2008	• Darwin space mission planned for launch 2015
• Sofia begins full science operations approx. 2009	• Thirty Meter Telescope (TMT) first light expected after 2015
• Space Interferometry Mission planned for launch 2009	• Giant Magellan Telescope first light ?
• HST, FUSE, Chandra, XMM-Newton, ...?	• OWL: attain 60-m by 2015? 100-m by 2021?

2. INSTRUMENTAL NICHES

While the instrumental capabilities summarized in Table 1 are impressive, two areas would appear to be un- or under-represented: spectroscopy over wide fields of view and at high spectral resolution. In addition, though many large, ground-based telescopes are currently developing or have recently commissioned adaptive optics systems, second generation, multi-conjugate systems should still be very competitive in the decade following 2010. Medium resolution spectroscopy over very large fields of view (several degrees) is the goal of the wide-field telescope (WFT). I propose that high resolution spectroscopy from the optical ($0.4-1.0\,\mu$m) to the mid-infrared (MIR; $5-25\,\mu$m) and advanced, adaptive optics imaging and spectroscopy in the near infrared (NIR; $1-5\,\mu$m) be the goals of the narrow-field telescope (NFT). These capabilities need not exclude direct imaging in the optical or mid-infrared, but other facilities, especially in space, will have unsurpassable advantages in imaging, so it would appear sensible that imaging be secondary to spectroscopy, except in the NIR.

The NFT should be optimized specifically for high resolution spectroscopy and for observations in the infrared. Since the NFT need not fulfill all of the capabilities of a general purpose telescope given that it is only part of the entire project, this optimization of the NFT does not represent any limitation for the project as a whole. The NFT should incorporate fast, tip-tilt guiding as a default mode, perhaps by incorporating an active secondary as at the MMT (Lloyd-Hart et al. 2000; Riccardi et al. 2000), since this will benefit spectroscopy and imaging at all wavelengths. The NFT should be optimized for the infrared, with protected silver mirrors. Silver mirrors will eliminate the possibility of observations below 4000Å, but enhance the efficiency in the infrared. The NFT should have a modest field of view of several arcminutes ($\sim 5'$) for imaging in the optical and multiple integral field units in the NIR. To be competitive, the NIR instrument must have multi-conjugate adaptive optics, at least as envisioned for GSAOI[3], the Gemini South Adaptive Optics Instrument and perhaps including multi-

[3]See http://www.mso.anu.edu.au/gsaoi/

mode lasers as proposed for CFHT's VASAO[4]. In the MIR, high resolution spectroscopy will help counter the atmospheric emission that is so detrimental to ground-based imaging at these wavelengths. It is unclear whether the MIR instrument requires any imaging capability beyond that needed for target acquisition, since space-based instruments will be overwhelmingly more sensitive for imaging, e.g., JWST.

While high resolution spectroscopy may not be a unique capability for the NFT in the decade following 2010, it is not clear from the perspective of the Mexican astronomical community that this is such an overriding factor as it is in communities with access to a wider variety of large telescope facilities. It is also important to foster what has and can be done well. Even so, there will be few facilities almost entirely dedicated to high resolution spectroscopy.

A logical optimization of high resolution spectroscopy might be to dedicate it to the infrared. Practically, however, a dedicated infrared facility would be un- or under-utilized in San Pedro Mártir of order 30% of the time (Warner 1977; Erasmus & van Staden 2003; Tapia 2003). Therefore, to best utilize all of the time available, an optical instrument is worthwhile, apart from the fact that one of the most exciting scientific opportunities exists in optical spectroscopy to follow up the GAIA and LSST experiments.

3. GALAXY EVOLUTION: WHAT, WHEN, HOW, AND WHY?

A useful simplification of galaxy evolution is to consider it as two stages: mass assembly and mass transformation. To a certain extent, mass assembly occurs before mass transformation, but this order is by no means necessary and both stages may occur throughout the history of a galaxy. Indeed, our own Milky Way is still accreting matter, most famously at present through the ingestion of the Sagittarius dwarf spheroidal. This is an example of (late-time) mass assembly only, since the Sagittarius dwarf spheroidal is much less massive than the Milky Way and devoid of gas that may be transformed into stars. Any mass transformation associated with this event, through gravitational perturbation of the gas in the Milky Way's disk, involves mass already belonging to the Milky Way. In the distant future, the only evidence remaining from this event will be the presence of a collection of stars, representing a small fraction of the Milky Way total, sharing common kinematic characteristics and chemical compositions (the Sagittarius dwarf contains several stellar populations). If the Sagittarius dwarf contained gas or if it were more massive, the result could be considerably different.

The scientific emphasis for the WFT will be to determine what objects are evolving and at what epochs in the past, thereby determining what evolution takes place at different epochs. Broadly, then, the WFT will be dedicated to studying the mass assembly of galaxies and those aspects of mass transformation that can be studied at medium spectral resolution, such as chemical evolution, large scale kinematics, and dynamics. Its targets will therefore be galaxies and quasars as probes of large scale structure and cosmology.

While the assembly of mass in galaxies accounts for a substantial fraction of galaxy evolution, it is not a complete picture. Galaxy evolution would be comparatively dull if collecting together gas were all that happened. It is also necessary to understand how and why mass is transformed from gas to stars, eventually to be partially returned again as enriched gas that will perhaps undergo further transformation, provided it remains within its host galaxy. Spectroscopy at high spectral resolution is the tool required to study the processes responsible for mass transformation in galaxies, especially if it can be coupled to high spatial resolution. Consequently, the NFT should focus its attention on stars, interstellar gas and dust, and star formation as well as the effects these have on their host galaxies. Although not normally considered the domain of galaxy evolution, these processes associated with stars, the ISM, and dust are precisely the agents responsible for matter transformation and, hence, galaxy evolution, once mass assembly is complete or between episodes of mass accretion. Without them, our understanding of galaxy evolution is incomplete.

In this sense, the WFT and NFT together can be considered as *a tool* to study galaxy evolution. In the division of labor, the NFT considers the questions how? and why? while the WFT confronts the questions what? and when?; between them exploring the full range of issues involved in galaxy evolution.

4. HIGH RESOLUTION SPECTROSCOPY

Line widths of a few km s^{-1} are observed in a wide range of systems. Micro-turbulent velocities in stellar atmospheres, velocity dispersions in giant molecular clouds and locally in galactic disks, and thermal velocity widths of common ions in ionized gas, are all of order a few km s^{-1}. Consequently, 10^5 is a convenient spectral resolution for the study of a wide range of problems in Galactic and extragalactic astronomy relating to stars, gas, and dust.

[4]See http://www.cfht.hawaii.edu/VASAO/

Given the wavelength range under consideration, optical to MIR, at a large telescope it is necessary to note that high resolution spectroscopy incurs an additional difficulty once the diffraction limit is reached. In this case, the optimal slit width becomes wavelength dependent and it is impossible to design a spectrograph to perform efficiently at a given spectral resolution at all wavelengths. In practice, this difficulty must only be confronted in the MIR spectral range, where the spectrograph is then designed for optimal efficiency up to some limiting wavelength, beyond which a lower resolution will be required to maintain the instrument's efficiency.

Generally, the type of instruments required would allow both classical echelle and long-slit modes since the objects of interest are both point-like and diffuse (stars and gas, respectively). Ideally, these instruments would also have multi-object spectroscopy and imaging capabilities. Such instruments are unlikely to achieve the extremely high, long term, spectral stability required for planet searching, but it is not clear that this technique will still be such a dominant competitor in the era under consideration (see Table 1). Examples of optical spectrographs with some of these capabilities are ESO's UVES (Dekker et al. 2000) and CES[5], the AAO's UCLES (Stathakis et al. 2000), or the OAN-SPM's MES (Meaburn et al. 2003). There is no need to offer medium or low resolution optical spectroscopy since that will be available at the WFT. Examples of NIR spectrographs with some of these capabilities are ESO's CRIRES (Käufl et al. 2004)[6] or Gemini's proposed HRNIRS[7]. As already noted, the NIR instrument should allow multi-conjugate adaptive optics imaging at least competitive with Gemini's GSAOI [3] and diffraction limited spectroscopy, as planned for the Gran Telescopio Canarias' FRIDA instrument (López et al. 2006). The NIR instrument could offer the option of medium resolution spectroscopy, if that is not available at the WFT. An example of a working, high resolution, MIR spectrograph with the characteristics envisioned here is the TEXES instrument (Lacy et al. 2002), used at McDonald Observatory and the NASA IRTF. Low resolution MIR spectroscopy will not be competitive with space-based facilities. SOFIA will foster further development of high resolution spectroscopy in the MIR.

Ideally, the foregoing suite of instruments would be installed permanently and available on-demand, permitting the efficient matching of observing conditions with instrumental options. Such an arrangement should not only favor more robust and reliable instrumentation, but also permit the definition of key projects that could be undertaken when time was available and observing conditions suitable.

5. SCIENCE THEMES

5.1. *Planets and exoplanets*

The chemical composition, physical conditions, structure, and kinematics of planetary atmospheres within the solar system may be studied via high resolution spectroscopy in the near- and mid-infrared. There remains hope that high resolution spectroscopy in the optical will permit transit spectroscopy of the atmospheres of exoplanets (e.g., Seager & Sasselov 2000; Fortney 2005). In practice, high resolution spectroscopy is necessary to separate telluric features from the similar signatures expected in the objects under study.

High resolution spectroscopy in the NIR could be particularly useful for searching for low-mass, terrestrial planets around M and L stars.

5.2. *Stellar Atmospheres and Stellar Structure*

High resolution optical spectroscopy on a large telescope would enable the study of asteroseismology throughout the HR diagram, identifying pulsation modes and thereby constraining theories of stellar structure in ways that are difficult to study by other means. In general, unknowns in stellar evolution propagate through our understanding of a variety of processes, from the stellar-ISM interaction and its effects upon star formation to the the chemical evolution of galaxies and even their integrated properties, such as colors.

The physics, especially that of stellar winds and mass loss, as well as chemical composition could be studied in stars within the Milky Way and Local Group. The study of chemical compositions, in particular, would have an important influence on our understanding of galaxy evolution, directly in the very nearby universe, e.g., Venn et al. (2004), and by inference well beyond. Infrared spectroscopy of late-type stars would be invaluable for the study of mass loss from these stars and the implications for mass return to the ISM. Another propitious avenue of study would be dust formation, particularly around hot stars, such as WR stars, where the process is particularly poorly understood.

5.3. *ISM*

The interstellar medium offers a variety of important problems whose solutions could be sought

[5]See http://www.ls.eso.org/lasilla/sciops/3p6/ces/
[6]See also http://www.eso.org/instruments/crires/
[7]www.noao.edu/noao/noaonews/sep04/pdf/79ngsc.pdf

via high resolution spectroscopy. As discussed by Ferland (2003), the recombination/collisional abundance problem is a fundamental uncertainty concerning the interpretation of chemical abundances in ionized nebulae, from which we obtain a significant fraction of chemical compositions for matter throughout the universe. Deep, high resolution spectroscopy, ideally also including kinematic and spatial information, is required to solve this problem.

The ISM in the Milky Way, and presumably in all other galaxies, has a collisionally ionized hot component whose study is now relatively common using X-ray satellites. Despite the observational advances and despite its importance regarding the energy equilibrium, even on galaxy-wide scales, the physics of the contact surfaces is poorly constrained in many cases (e.g., Soker & Kastner 2003). Although satellite observations in the UV and X-ray ranges will be necessary to study the principal aspects of this problem, optical and infrared spectroscopy should provide essential complementary data, particularly regarding chemical abundances, via observations of coronal emission lines.

Diffuse interstellar bands were discovered many decades ago (Heger 1922; Merrill 1934). Deep, high resolution spectroscopy may offer a means of identifying the carriers (e.g., Kerr et al. 1998), none of which have as yet been identified. Studies of dust, generally, could benefit from high resolution spectroscopy in the MIR.

Another area where significant contributions could be made is in the kinematics and composition of the ISM, both in emission and absorption, both within the Milky Way and beyond, via high resolution spectroscopy from the optical to the MIR.

High resolution spectroscopy in the MIR can provide unique information about the chemical composition and kinematic structure of molecular clouds (Lacy et al. 2002). The conditions in molecular clouds, cold temperatures, molecular species, and high obscuration, require high resolution in the MIR to resolve the lines.

The kinematics of compact and ultra-compact H II regions could be studied via high resolution MIR spectroscopy. Since these regions are generally only observable via radio continuum or recombination line techniques, both inherently based on hydrogen, the kinematic information available is limited. The study of ionized heavy ions, such as Ne^{+}, would provide the same velocity resolution as available for unobscured nebulae studied in the optical.

Diffraction-limited NIR imaging and high resolution spectroscopy would also likely have a large impact upon studies of jet-launching mechanisms in objects as diverse as young stellar objects, planetary nebulae, and perhaps even galactic nuclei. Likewise, the disks around young stars are another obvious target for NIR imaging and spectroscopy.

5.4. *Star Formation*

NIR imaging is a traditional tool for studying star formation and, with adaptive optics, it can be profitably extended (with care) to the entire Local Group. Including the L and M bands, high mass star formation should be more easily studied. Similarly, studies of resolved stellar populations from within the Milky Way to beyond the Local Group are accessible.

The NIR is the wavelength regime of choice for studying the mass distributions of low mass stars. Likewise, much of the characterization of pre-main sequence stars will also be based upon NIR imaging.

5.5. *Structure and Evolution of the Milky Way*

The GAIA satellite will provide us with an unprecedented view of the structure and evolution of the Milky Way via distances, kinematics, and metallicities for up to 10^9 stars (including several million in the Magellanic Clouds). The LSST will complement this effort by compiling a vast database of light- and position-variable sources, both Galactic and extragalactic. Both of these missions will require very substantial follow-up spectroscopy to make the most of their information. GAIA, for example, will provide stellar metallicities, but not the detailed chemical compositions required to determine whether kinematic groups arose from a single parent body or several. Likewise, the LSST will identify enormous numbers of variable sources, but their detailed study and understanding will depend upon other facilities. Efficient, high resolution optical spectrographs on large telescopes are the ideal instruments to mine these vast databases. Of the instrumentation proposed herein, high resolution optical spectrographs are expected to be the most common elsewhere. Nonetheless, the opportunities are likely to be so vast that they are unlikely to receive as much attention as would be worthwhile. Indeed, the task is so great that it would be sensible to have a UVES-style multi-object spectrograph on the WFT for use as a continuous survey instrument. As regards follow-up for LSST, since it is likely to detect hitherto unknown phenomena and sources, high resolution spectroscopy across the largest wavelength interval possible is likely to prove crucial in unraveling those mysteries.

5.6. *Galactic Structure*

NIR spectroscopy and imaging presents perhaps the best opportunity to study the structure and evolution of galaxies and their constituents in the nearby universe. Adaptive optics imaging will permit the study of galactic structure out to ($z \sim 1$). Since the NIR is only modestly affected by reddening and recent star formation under most circumstances, given its sensitivity, it is a good wavelength range in which to measure masses of ionized gas, stars, and galaxies.

Diffraction-limited NIR imaging would permit innovative studies of the structure of AGN, quasar hosts, and galactic nuclei. Coupled to high resolution spectroscopy the study of the kinematics and chemical composition (via absorption lines) of the surrounding galaxy would be possible at spatial resolutions not attempted so far.

With approximately-matched high resolution spectroscopic capabilities in the optical and NIR, the kinematics and chemical composition of QSO absorption line systems could be followed to considerably higher redshifts with concomitant advances in our understanding of the chemical evolution of the early universe.

6. CONCLUSIONS

The general scientific themes considered above are kinematics, chemical composition, and structure. All instruments will contribute to our understanding of the structure and evolution of the Milky Way via studies of the kinematics and chemical composition of stars, their atmospheres, and their circumstellar envelopes. The infrared instruments will contribute to studies of star formation as well as the structure and chemical composition of molecular clouds, primarily within the Milky Way, but also to a limited extent within the Local Group. The optical and NIR instruments will contribute to studies of exoplanets. All instruments will contribute to the study of stellar atmospheres, interiors, and mass distributions, from within the Milky Way to beyond the Local Group. All instruments will contribute to studies of the ISM composition and kinematics, within the Milky Way and throughout the universe. The optical and NIR instruments will contribute to studies of galactic structure, galactic nuclei, and quasar absorption line systems. Finally, there will undoubtedly be discoveries not even contemplated here.

All of the foregoing will enhance our knowledge of stars, gas, dust, and galaxies, clarifying and quantifying the relationships between these components. It is these relationships that define how and why the processes that transform matter within galaxies act to produce the galaxy evolution we observe. The instrumental capability required to undertake these studies is high resolution spectroscopy covering the optical, near-, and mid-infrared and adaptive optics imaging and spectroscopy in the near-infrared.

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