SCIENCE CASE FOR 100-m TELESCOPE "OWL"

A. Planets and Stars

1. Extra-solar planets: "Planets Everywhere"

OWL will be a uniquely powerful facility for the study of extrasolar planets, from detection, through characterisation by spectroscopy, to elucidating their evolution. Parts of this topic may be accessible to smaller telescopes; however only OWL will have the critically important ability to *discover terrestrial planets by direct imaging* and to characterise them by *spectroscopy of their atmospheres*. This is an undertaking which is *not* practicable for a significantly smaller facility, but one which is of the utmost importance both scientifically and philosophically. For this reason the potential contribution of OWL to the study of extrasolar planets is presented here in some detail.

1.1 Detection and study of Terrestrial Planets ("Exo-Earths").

1.1.1 Challenges of detecting exoplanets

Nearby planets, even small ones like Earth at Earth-like distances from the parent star, are relatively bright sources for OWL and their detection at distances of a few tens of pc would be relatively easy were it not for the glare from the parent star. In the case of the Solar System, the Sun is $\sim 10^{10}$ times brighter than the Earth at visible and near-IR wavelengths. In order to stand any chance of success it is therefore necessary to minimise the effects of this glare by concentrating the light of both the planet and the star as much as possible.

1.1.2 Adaptive Optics and OWL's image structure

OWL will be equipped with state-of-the-art Adaptive Optics (AO) systems to compensate for atmospheric seeing and produce a near-diffraction-limited image or image core. The AO system may be expected to deliver Strehl ratios S (peak image brightness relative to that in a perfect image from the telescope) of several to many tens of percent. In the near-infrared (NIR) i.e. wavelengths from 1 to 5 μm, values near 90% should be attainable.

Applied to a nearby solar-type star the AO will produce an image which comprises several components. A central "spike" resembling a diffraction-limited image contains $\lesssim$S% of the total light, less a modest fraction which is diverted into the other, wider-spread components of the intrinsic telescope point-spread-function (PSF: see below). The "spike" is surrounded by a residual halo (the "AO halo") containing the remaining $\sim$ (100-S)% of the light distributed like an unmodified seeing disc, *i.e.* with a generally Lorentzian (Cauchy) radial distribution (F. Rigaut, private communication 2001). The halo overlies, and, within the seeing radius, dominates, the fainter wings of the "intrinsic" PSF of the telescope. This last combines the light distributions produced by the large-scale optical properties of the telescope, the central diffraction pattern, light scattered by small-scale imperfections and dust on the optics, and diffraction from geometric edges. Geometric diffraction is dominated by the cross-shaped pattern generated by the structure supporting the secondary mirror.

The wavelength range where planets may best be detected and studied with OWL is probably the near infrared J band, centred at 1.25 μm, and the far red Z and I bands, extending down to 700 nm. AO performance is expected to be good at J, where achievable Strehl ratios S should approach 90% and strong spectral features of water are available as diagnostics. The Z and I bands are less favourable for AO but the latter contains the critical O_2 "B" band (see below, "characterising a terrestrial exoplanet").

The detailed structure of the haloes in AO-corrected images is still being explored. At large radii (well outside the central diffraction pattern) they are composed of the rapidly-varying ... the rapidly-varying diffraction-spot-sized "classical" speckles, well known to observers on large telescopes in the visible wavelength range. However closer to the centre, apparently confined to the first 2 or 3 diffraction rings, less well understood "superspeckles" occur. These are larger, brighter, less rapidly variable, and therefore less likely to average out on a long-exposure image. The super-speckles are not explained by current numerical models of AO systems. However on real images the superspeckles appear to be confined to the inner regions, overlaying the first 2 or 3 diffraction rings. However, because they appear to be confined to the inner regions of the image, at the wavelengths of interest they should not occur more than $\sim$ 10 milli-arcsec (mas) from the image centre, whichcorresponds to only 0.1 AU at a distance of 10 pc.

1.1.3. Planetary Imaging with OWL

The relatively large angular separation between the image of a habitable planet and the central diffraction peak of its parent star is what will permit OWL to detect a terrestrial-like exoplanet in the face of the stellar glare. At an angular separation of 100 milli-arcsec only the natural sky background, the wider scattering components of the intrinsic PSF, and the AO halo, contribute to the background against which the planet must be seen. The AO halo dominates but nevertheless it is dilute enough to allow the detection of exoplanets.

At any given distance from the solar system the parameter space over which target exoplanets are accessible to OWL will be bounded by two effects. The brightness of the starlight reflected by the planet falls off with increasing orbital distance from its parent star, which limits the detectability of an exoplanet very distant from its parent star, even though it is well separated from it. At the other extreme the bright inner structures of the stellar image (superspeckles, diffraction rings *etc.*) will drastically reduce sensitivity at angular separations $\lesssim$20 mas. This correponds to an orbital radius of 1 AU at 50 pc, 5 AU at 250 pc or 50 AU at 2500 pc. In the latter two cases attenuation by distance from Earth, and the low level of illumination by the parent star, combine to imply that only a self-luminous exoplanet (see below, Young Jupiters) could be detected.

Nevertheless OWL is capable of a vast range of exoplanetary investigation, covering planets both outside and inside the star's "Habitable Zone" (HZ), the small range of orbital radii within which surface water will be liquid, and therefore favourable to the emergence or existence of life approximately as we know it. (The sun's HZ is about 0.15 AU deep, centred at 1AU).

Figures 1 and 2 show a numerical simulation of an star image exposed for 10^4 sec in the J band. Fig. 1 shows a 3$''$ square area around the star and Fig. 2 offers a closer look at the central parts with the starlight subtracted, revealing two members of the star's planetary system superimposed on an image of the noise distribution in this portion of Fig. 1 (see caption).

[IMAGE: THE PSF OF A SUN-LIKE STAR AT 10 PC]

Caption: A numerical simulation of an OWL image of a star. Total exposure time is 10^4 s in the near-IR J band (central wavelength 1.25 μm) The image is displayed on a logarithmic scale to show the complex structures present around the central peak, against which background a planet must be detected. The components described in the text are apparent: the compact central spike, partly lost to limited dynamic range in the reproduction, is surrounded by the soft, fuzzy AO halo. Further out can be seen the diffraction structures from the secondary mirror supports and the segmented primary and secondary mirrors. Their wedge-shaped appearance results from rotation of the telescope relative to the sky during the exposure. The simulation assumes uncorrected seeing of 0.″4, an AO system delivering 90% Strehl, a telescope meeting the proposed specifications of OWL and realistic detector properties. The image is actually of a solar system comprising a sun-like star at 10 pc, with two planets, which are visible on our figures only after further processing (see Fig 2.)

[IMAGE: Simulated image of the Sun at 10pc with Jupiter and Earth.]

Caption: The simulated solar system from Fig. 1 with the star subtracted out, revealing Jupiter-like and Earth-like planets orbiting at 5 and 1 AU respectively. The system is seen from their ecliptic pole. The cross-sectional plots show that the exo-Earth is detected with signal-to-noise ratio (SNR) ∼20, the exo-Jupiter at SNR ∼500. Evidently the latter would be a relatively easy target for low- to moderate-resolution spectroscopy, and a spectrum of the exo-Earth could be secured with some effort (the simulation suggests that for spectral resolution of 1000, an SNR of 5 should be achievable in a few nights.)

1.1.4. Detecting the exoplanets

The simulation illustrated in Figure 2 represents a solar system containing a Jupiter-like and an Earth-like planet. The central star has been subtracted, to permit the planetary images to be seen. The star's location is apparent on the image from the enhanced noise underlying the centre of its image and its diffraction spikes. This subtraction is not in principle necessary for the detection, but in practice a simple coronagraph would probably be necessary to protect the detector from the high flux levels in the core of the stellar image. Note that if by chance a planet were concealed under one of the diffraction spikes, the rotation of the (alt-az) telescope relative to the sky (or equivalently, of the PSF structure, especially the diffraction spikes, relative to a detector array in an instrument supported on a rotator) will soon unmask it.

Slightly less tractable would be the case of a planetary system seen nearly edge-on. In this case the planet will spend a significant fraction of the time closer to the star than its maximum elongation: it is necessary to wait a few months until its orbital motion takes it clear once again.

It is obvious that a serious programme of exoplanet detection and characterisation will require both preparation and persistence, but will in addition yield other scientific rewards. Perhaps 1/3 of nearby solar-type stars are single, and only those multiples with very wide separation are likely to be good prospects for a Sun-like solar system; in the others the incidence and effects of binarity will need to be quantified. "Hot Jupiters" orbiting very close to the star are of special interest: these planets, which have probably reached their location by inward migration, are likely to have disrupted the orbits of any pre-existing terrestrial planets which may have been encountered en route.

1.1.5 Characterising a "terrestrial" exoplanet

The near-infrared J band, which is nearly optimum for the detection of exoplanets, is bounded on both sides - and contains - strong spectral absorption features from water in Earth's atmosphere. Liquid water is arguably essential for carbon-based life with a generally terrestrial-like chemistry, so these features are an extremely important potential diagnostic of conditions on the planet's surface.

[IMAGE: Earth atmospheric transmission spectrum from $\sim$ 500 to 1600 nm.]

Caption: The absorption spectrum of earth's atmosphere, showing the diagnostic absorptions of O_2 in the far red and H_2O in the NIR. Other possible diagnostics (located in the visible, where AO performance is likely to be less satisfactory) include surface absorption features, e.g. of chlorophyll.

In the centres of the stronger absorption bands saturated lines will obscure the signal from an exo-Earth. However in the wings of the bands numerous, narrow, unsaturated lines, which are still strong features, will move in and out of co-incidence with the same lines in the atmosphere of the exoplanet because of the changing doppler shift (up to $\sim$ 50 km s^{-1}) as the two planets move around their respective suns. This shift can be employed to allow the planetary spectral features to be detected spectroscopically, even on low-dispersion spectra, and an indication of their strength to be obtained.

Similar techniques can be used to seek for the "B" absorption complex of oxygen at 760 nm in the far-red optical wavelength range. As has been extensively discussed in other contexts, significant amounts of free oxygen in the atmosphere of an exoplanet would be a strong indicator of the presence of photosynthetic biochemistry, *i.e.* of life. Its absence, however, is not conclusive evidence for an abiotic world. Photosynthesis is not essential to life, which on Earth managed happily without it for half of the planet's history.

An exoplanet with appropriatly exotic chemistry would be quite likely to exhibit other, perhaps totally unexpected, spectral features. It is clear that such studies will constitute one of the most exciting potential applications of OWL.

1.2 Jovian planets "hot", "warm" and "cool."

1.2.1 Mature (non-self-luminous) exo-Jupiters

Numerous Jovian sized planets very close to their parent stars ("hot" Jupiters and super-Jupiters) have been discovered by radial velocity observations (REF NEEDED). These objects, which have probably migrated to their present locations after forming at much larger distances from their parent star, are in very different environments from the gas giant planets in our own solar system, and will in any case be impossible to resolve from the glare of their parent stars.

At somewhat larger orbital radii, approximating that of the HZ for a solar type star, several "warm" Jupiters are now known (REF NEEDED). A few exoplanetary systems are now know to harbour "cool" Jupiters, orbiting well beyond the outer edge of the HZ (see below for the example of ν Andromedae) at 2-4 AU. Our own solar system offers the only known example of a "normal" ("cold"?) Jupiter, with orbital radius of 5 AU. It shoudl be noted that the present predictions assume a Jupiter-like reflectance spectrum for all "Jovian" exoplanets (except the "Young Jupiters" discussed in sections 1.2.3 and 1.2.4.

Out to $\sim$ 100 pc OWL will be capable of direct imaging of "normal" Jovian planets orbiting solar type stars at distances typical of gas giants in our own solar system. "Warm" Jovian planets (orbiting at $\sim$1 AU) will be observable out to perhaps 50 pc.

Indeed, OWL will secure *spectra* of distant giant planets out to $\gtrsim$20 pc and of "warm" giants out to $\gtrsim$50 pc. Such spectra will enable a number of critical studies. The nature of the upper-atmosphere clouds particles can be determined (*c.f.* Marley *et al.*, 1999 Ap J, 513, 879), secondary species such as NH_3 and CO can be utilised as tracers of atmospheric circulation via their chemistry. Deuterated molecules (with lines near 2.4, 4 and 8 - 10 μm) can be used to determine deuterium abundances. These last enable a critical determination of the planetary mass, since if this exceeds 13 M_J deuterium will be depleted as a result of nuclear burning in the planetary core. This will require detection of bands which depress the continuum by less than 1%, a taxing but possible problem for OWL which is probably inaccessible to lesser telescopes.

1.2.2 Earth-like moons in the Habitable Zone

Figure 3 illustrates a system which contains Jovian planets approximating to all of the above categories: the known planets of ν Andromedae include a "hot", a "warm" and even a (reasonably) "cool" super-Jupiter (REF NEEDED).

[IMAGE: RV plot of υ And showing trace of both "hot" and "warm" Js].

Caption: Measured radial (line-of-sight) velocities of the nearby solar-type star υ Andromedae, showing the complex variations remaining after the strong effect of a $\sim$1M_J planet orbiting 0.06 AU from the star (period 4.6 d: a "hot" Jupiter) has been removed. The remaining variations show the slower effects of planets of mass 2 and 4.6 M_{Jup}, orbiting at 0.8 AU (in 241 d: a "warm" super-Jupiter) and 2.5 AU (a "cool" super-Jupiter which orbits in 1267 days). At υ And's distance of 13.5 parsec, these two strongly-illuminated outer planets will be readily observable with OWL, even in spectroscopic mode.

Systems somewhat similar to υ And may offer potential exobiological environments of an unusual sort: planet-sized (terrestroid) moons of "warm" Jupiters orbiting in the Habitable Zone. An Earth-sized moon of the middle planet of υ And would be too close to its parent super-Jupiter to be resolved by OWL in imaging mode, but the parent might be a bright enough target to allow medium-to-high resolution spectroscopy to be used to detect the reflex motion of the Jupiter arising from its terrestroid moon.

For an Earth-mass moon orbiting a Jupiter-mass planet at the same distance as the moon is from Earth, the reflex velocity range is $\sim\pm$ 60 m s^{-1} over a period of $\sim$ 1 day. At 5 pc OWL will secure spectra of the parent planet at resolutions of a few $\times$ 10^4, with SNR $\sim$20, in a couple of hours. To detect the reflex motion due to the planet would require a long observing campaign ($\sim$600 hours in all) acquiring many such spectra. These would be analysed in phase bins around a hypothetical orbit, after accumulating enough spectra to build up the SNR to the required level ($\sim$100 per pixel per phase bin). [AT 300-1000 HRS I FEAR THIS IS TOO LONG A PROGRAMME TO BE REALISTIC]

Unfortunately ν And b is slightly too close to its F6IV primary for habitability, and in any case has an orbital eccentricity of ~ 0.4, suggesting past experiences inimical to the survival of life in its vicinity. Nevertheless its presence indicates that a class of "warm" Jupiters with terrestroid moons may well exist and clearly deserves verification using OWL.

1.2.3 Young orbiting Jovian planets

Young Jovian planets are luminous in their own right (irrespective of reflected illumination from any parent star). The old (*i.e.* non-luminous) exo-Jupiter shown in Figure 2 has magnitudes around $V = 26.3$ and $J = 25.2$, purely from reflected starlight, but a 1 Gy-old 5 M_J exoplanet (which would have about the same diameter as a 1 M_J object) would have $J = 18.9$ from its own emission at the same distance of 10 pc. This would be easily observable with today's telescopes in the absence of a parent star and amenable to very-high-resolution spectroscopy with OWL, or indeed with a rather smaller telescope, even in the star's presence. A 1 M_J exoplanet of this age would be much cooler and fainter, at $J =$ 23.9, but still a relatively easy target for medium-resolution spectroscopic study with OWL.

However *imaging* of Jupiters and super-Jupiters using OWL will permit the detection of 1 My-old, 1 M_J objects down to 2 or 3 AU from (relatively unobscured) parent stars in the nearest star-forming complexes in Taurus, Lupus, Chamaeleon and Corona Australis, and proportionately fainter (smaller, or older) objects at larger orbital radii. More massive objects will be relatively more readily detected at all ages up to several Gy.

Jovian planets of known, rather greater, ages will be detectable around stars in the Pleiades (120 pc distant, 100 My old) and Hyades (46 pc distant, 1 Gy old), in addition to field stars of less well-determined ages in the solar neighbourhood out to more than 100 pc.

OWL will therefore permit the study of Jovian planets of a variety of sizes and ages, and will consequently permit the rigorous verification of theories of the formation and evolution of large planets in a range of environments. It should be noted that a significantly smaller telescope would be seriously limited in this work; the distances of the available clusters and star-forming complexes place them beyond the reach of, say, a 30m facility except for the study of the largest, most distantly-orbiting, super-Jupiters.

1.2.4 Free-floating "planets": the bottom of the stellar Initial Mass Function?

Not all planetary sized objects are in orbit around other stars. Young, free-floating planets (or small "brown-dwarf" substellar objects) have recently been detected in the region of the Orion nebula at 500 pc (SEVERAL REFERENCES AVAILABLE/NEEDED): such objects pose a much more tractable observational problem than planets close to stars. Figure 4, showing these objects, was secured with the 3.8-m UKIRT: OWL has at least 50 times UKIRT's range and can therefore, extinction permitting, trace these results of the fragmentation and collapse process of molecular clouds in young star forming regions (SFRs) across most of the galaxy. Indeed, young objects at the hydrogen-burning mass limit should be observable out to Andromeda.

Caption: A near-infrared image of the Orion nebula near θ^1 Ori, in which planet-like objects down to a few M_J can be detected.

The frequency and characteristics of young isolated sub-stellar objects as small as Saturn could be determined in star forming regions out to several kpc. Studies of such objects will define the lower end of the initial mass function (IMF) for cloud fragmentation in a wide range of star-forming complexes and will allow comparison with the evolution of similar-sized objects (*i.e.* young Jovian planets) which formed in orbits around stars. Because these objects can be studied out to considerable distances a number of different SFRs will be examined and relationships between the properties of the SFR and the sub-stellar (and stellar) IMF explored, for both captive and free-floating Jovian objects.

OWL will therefore enable us to study Jovian planets over a wide range of ages and circumstances, which will allow the evolution of their physical properties (effective temperature, gravity and chemical composition) to be studied from their birth until they evolve to objects as old as the solar system.

2. Our Solar System

2.1 Introduction: Seven planets, many moons and umpteen asteroids: a fulltime task for OWL?

All bodies more distant from the sun than Venus will be accessible to OWL. For most Solar System work it will be OWL's extraordinary resolution, its immensely powerful spectroscopic capabilities throughout the optical, near- and mid-IR, and its ability to secure deep, high-resolution images quickly and efficiently which will lead to a revolution in Planetology.

The main reason for OWL's great potential in this area of study is its extraordinary angular resolution, which will represent a quantum leap in our ability to examine the distant components of the Solar System. To illustrate this, the Table summarises the surface resolutions it will achieve:

Object	**Surface resolution (km)**	**Pixels across typ. disc**	**Notes**
(Moon	3m	$\sim 10^6$	illustrative...)
Mars	$\sim$2	3400	
Asteroids	3-7	$\sim$200	Ceres, Vesta..
Jupiter	8	$\sim$500	Galilean moons
Saturn	15	$\sim$300	Titan
Uranus	30	$\sim$25	Ariel
Neptune	45	$\sim$90	Triton
Pluto	60	$\sim$90	
(20,000) Varuna	63	$\sim$15	Large Trans-Neptunian Object

These resolutions offer a dramatic leap forward for solar system astronomy. OWL will fill the huge gaps which afflict our spacecraft-based knowledge of the surfaces of solar-system objects, doing the work of a flotilla of fly-by planetary probes. In particular the telescope will throw open the barely-explored field of long-duration monitoring of objects where changes with time are both expected and of interest to planetologists, at surface resolutions comparable to those offered by weather satellites of Earth.

It is clear that Observational Planetology could easily utilise a very large fraction of the telescope's time, and with a guarantee of commensurate scientific returns. Indeed, this is one field where we have a ready reckoner of costs and benefits against which to measure OWL's immense potential: the great and dramatic archive of data which has been returned by the probes and orbiters of the Space Programmes of the world, but which could readily be multiplied several times in size and scientific utility in a decade of work by OWL.

This yet again illustrates establishes OWL's potential as a scientific engine of unparalleled efficency and cost effectiveness.

In what follows we address illustrative areas where we believe that particularly dramatic new results are certain to be obtained, simply by way of illustration of the possibilities, which are far too rich and varied to be fully explored here.

2.2 The Master Atlas of the Solar System

Probes have mapped at least one face of a fair fraction of the larger component bodies of the solar system. However up till now only (expensive and complex) orbiters stand a chance of producing a complete map of any object. Conversely, how much can be missed in a simple flyby is well illustrated by Mariner IV's failure to detect the great valleys of Mars, arguably more important features than its impact craters for understanding its evolution and the dramatic significance of its ancient topography. Happily for the potential pressure on OWL observing time, Mars has been well served with orbiters with linear resolving capabilities comparable to (and in one case superior to) those likely to be offfered by OWL.

However beyond Mars is the asteroid belt, containing a few hundred objects quite large enough for OWL to yield important surface detail. Indeed as with most Solar-System bodies, spaitially resolved spectroscopy with a linear resolution of 2-8 km and almost arbitrarily high spectral resolution is also readily possible. We here summarise six areas in which major advances will occur.

1. *Large and nearby asteroids.* For the few hundred largest asteroids complete surface maps, showing topography and geological indicators at surface resolutions of a few km, will be obtainable in a few minutes of observation of each, spread over a few days or weeks (depending on the asteroid rotation properties and axis orientations). The same will be true of the important near-Earth and Earth-crossing objects, which, being often much closer, will be observable at much higher surface resolution than main-belt asteroids.

2. *Smaller asteroids.* Main-belt objects down to ∼10km across will be sufficeintly resolved to determine details of rotational period, sizes, shapes, axis orientations and approximate surface distribution of geological components.

3. *Moons, major and minor.* Of the the solar system's planetary satellites many are unstudied, while the majority are represented in our current databases by a few images taken at a distance by a probe in an orbit not optimised for that body. These data sets will be completed, or in most cases superseded, by OWL, with image sets offering near-complete multiwavelength surface coverage and in most cases superior resolution.

4. *Multiband Imaging and spectroscopy of Trans-Neptunian Objects (TNOs).* The larger TNOs will be resolved by OWL with many pixels across their disk: (∼15 at the J band in the case of (20,000) Varuna, one of the largest currently known). The OWL studies of the TNOs will determine whether cometary activity occurs at these very large heliocentric distances, and if so in what type of surface terrain. In the case of the larger TNOs, for which good quality mapping is possible, synopic studies over decade-long periods will allow the long term evolution of the surfaces to be followed.

   Spectroscopy of TNOs down to a few tens of km in diameter will be possible at spectral resolutions comparable or higher than the best spectra currently available for Pluto. This will identify surface ices and their physical states (mixture ratios, etc) and even accurate temperatures via the narrow 2.16μm feature of N_2. Such spectra will also allow geological mapping of the planetesimal surfaces and correlation of albedo features with specific materials.

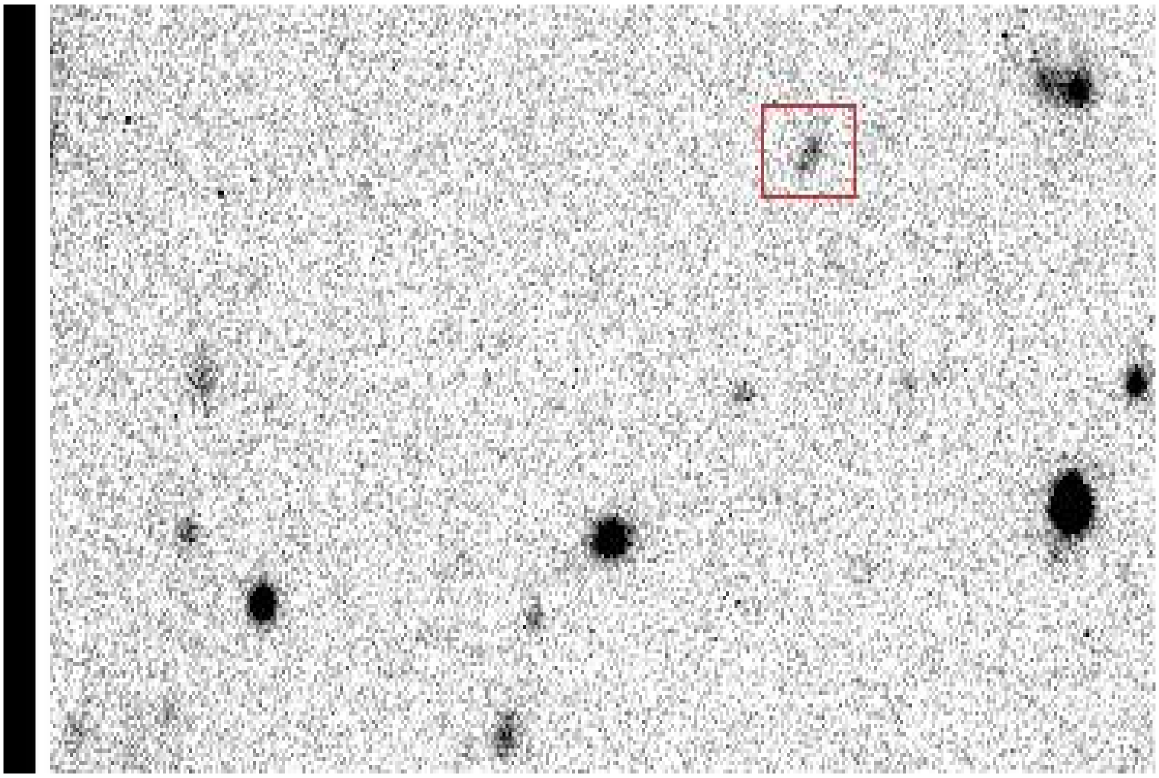
   A particular application, for which OWL is unlikely to have serious competition, is in spectroscopy of larger TNOs at resolutions around 10^5, which will permit the determination of the D/H ratios of the surface ices in these bodies. This ratio is known for the comets originating in the Oort cloud and it is of great interest to know whether the ratio is the same in the Kuiper Belt, which would imply similar thermal histories. The Oort cloud objects have higher D/H than do Earth's deep ocenas, and the question of whether the terrestrial hydrosphere was seeded from Oort or Kuiper belt is obviously of great interest.

5. *Binary Objects, masses and densities.* OWL's survey of the solar system will detect essentially *all* existing companion objects down to a few metres in diameter, in the Main Belt, and a km or so in the Kuiper belt. Orbital parameters will provide masses and the resolved images will determine diameters; from this information, densities can be

derived, which are critical to understanding the structure, composition and evolution of the small bodies.

6. *Sizes, shapes, surface and thermal properties.* OWL's ability to *resolve a large fraction* of the bodies in the solar system allows direct determination of shapes without the shape/albedo degeneracy which comes from unresolved lightcurve observations. This in turn constrains thermal models which can then be used to probe the bulk properties of the object via their sub-surface thermal conductivity (REFERENCE NEEDED). Non-spherical shapes provide limits on the density and strengths of materials required to resist self-gravitational collapse into a sphere. Images will reveal large scale surface inhomogeneties, to constrain impact histories.

It is clear that OWL will provide a database which will be an indispensable precursor to possible future exploitation of the raw materials offered by the asteroids.



Caption: The binarity of trans-Neptunian object 1998 WW31 was discovered by chance in 2001 during observations made for astrometric purposes.

2.3 Surface and atmospheric changes on other planets

Several solar-system bodies exhibit suface changes on timescales of days to years. Furthermore all the solar-system bodies with true atmospheres show, or will show when examined in the sort of detail OWL will offer, meteorological phenomena. These range from the rapid circulation in the great spot of Neptune, which frustrated interpretation on Voyager images, to the leisurely evolution of the Martian dust-storm season. All such studies will benefit immensely from OWL's capability to monitor changes on timescales from minutes to years, allowing us to study phenomena associated with the local equivalents of tropical storms or changes reflecting the impact of the solar cycle. We list four examples of surface and atmospheric studies which are of particular importance for planetology.

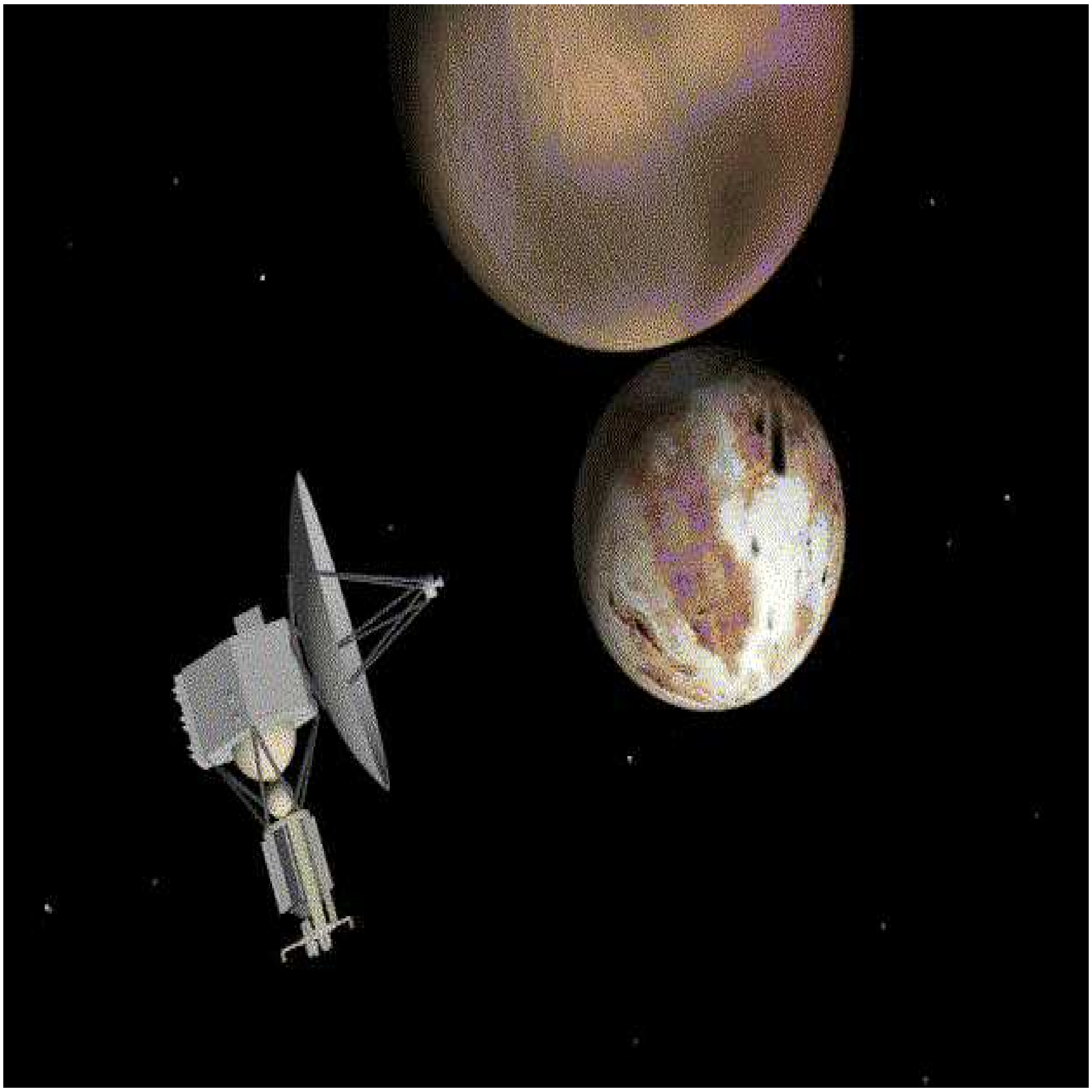
1. *Evolution of vulcanism on Io.* The images secured by OWL will offer between $\sim$900 (at visible wavelengths) and $\sim$100 (thermal IR) resolution elements across Io. In the visible and near-IR these images will be surpassed only by those secured on the nearer flybys of Galileo. Thermal IR images at these resolutions have never been secured. OWL will open a new era of vulcanism studies on this moon, greatly enhanced by the powerful spectroscopic possibilities of the huge telescope with its state-of-the-art intruments.

2. *Activation of the Centaurs.* The Centaurs are objects orbiting between Saturn and Neptune. They are similar in size to large asteriods, but have icy compositions more akin to comets and indeed are probably giant comet nuclei in orbits which are evolving inwards from the Kuiper belt. Most appear to be currently inactive, but the prototype, Chiron, is known to have periods of comet-like activity, developing a faint coma. At their distances of $\geq$ 10 AU they are far too cold for water to sublimate, so the cause of the activity of Chiron is a puzzle. OWL will permit the determination of detailed surface compositions for all the Centaurs. OWL will allow Centaurs to be monitored in detail as around their orbits, and will clarify the puzzling *lack* of activity seen so far on all but Chiron.

3. *Development of surface activity on Triton.* The structures generated by the gas geysers on Triton, and their influence on the evolution of the surface of that planetary-sized moon, will be readily discerned on OWL's $\sim$ 100 pixel-wide optical/NIR images. Again, thermal IR images and spectroscopy at a variety of wavelengths will greatly enrich this data set, and our resulting understanding of the processes at work on this fascinating world.

4. *The collapse of the atmosphere of Pluto.* It is expected that unvisited Pluto's current tenuous atmosphere will freeze in the 2000-2020 period (REFERENCE NEEDED). **If OWL is built soon enough** we will be able to follow that process in detail on images and spectroscopy with $\sim$100 resolution elements across the planet. Conversely, other large, distant bodies in eccentric orbits will be discovered in the meantime and it is likely that one or more of these will be approaching perihelion and entering the phase at which a frozen atmosphere will be rejuvenated by increasing solar heating.

   Indeed, given that the instrument suite of the telescope will certainly be enormously more varied and capable than can possibly be contemplated for NASA's on-again, off-again "Pluto Express" mission proposal, OWL might be seen as an acceptable replacement for that mission; only *in situ* measurements such as field strengths and trace gases remain to make a flyby attractive.

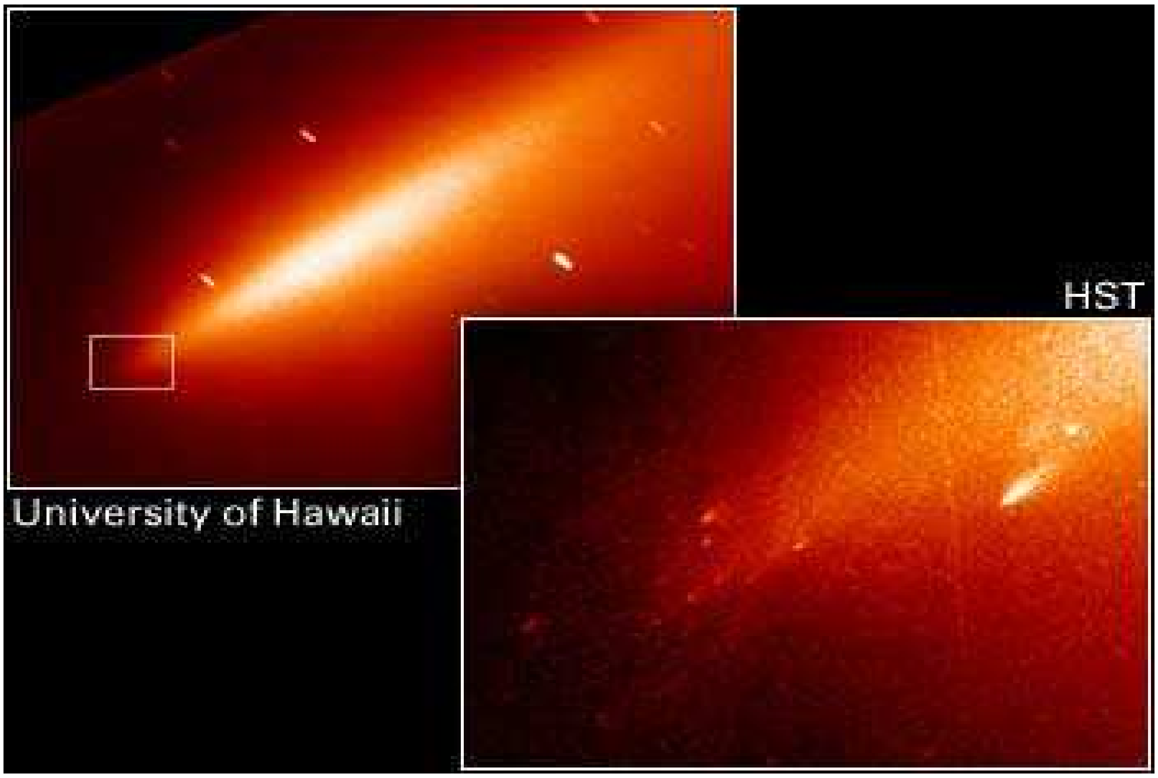


Caption: The hypothetical image of Pluto shown here as a background to the image of the P-K Express spacecraft has about one quarter as many resolution elements as would an OWL image of the Pluto-Charon system. Since the Pluto-Kuiper Express is unlikely to cost less than $250M, these observations alone could seen as jutifying a large part of the cost of the telescope.

2.4 The outer solar system and the Comets: fossils of the proto-planetary nebula

The size distribution of objects in the outer solar system constrains models of planetesimal accretion in the early solar nebula and the subsequent collisional erosion of the surviving planetesimals once the giant planets had formed. This distribution is not well known, even for the larger objects, but ground based searches with 8m class telescopes and possible future dedicated facilities will resolve this issue for objects larger than about 50-100km. OWL will make crucial "pencil-beam" surveys to detect objects orders of magnitude fainter, probing the trans-Neptunian size distribution down to objects less than 1km in size ($V\sim35$ at 40AU), thereby linking objects in the present Kuiper belt with the nuclei of observable short period comets.

Long period comets are believed to have formed at 10-20AU from the Sun before being ejected into the Oort Cloud (REFERENCE NEEDED). By following their evolution as they retreat from the Sun and de-activate, OWL will be able to determine the size distribution of long period comet nuclei without the uncertainties brought on by unresolved low-level activity at the (10-12AU) heliocentric distances to which they can be followed at present. Observing the fragments of cometary break-up such as occurred with comet LINEAR in summer 2000 is at the limit of present telescopes, but after such an event OWL will probe the sub-nuclear structure of the parent: are comet nuclei composed of discrete and heterogeneous sub-nuclei?



Caption. The nucleus of Comet LINEAR disintegrated in July 2000. The Hubble telescope and the 8m VLT were able to follow the fragments for a few days before they faded into invisibility. OWL would observe much smaller fragments, providing spectra to probe the internal physical and chemical structure of the comet nucleus.

Ideally we would like to begin watching "new" long period comets while their surfaces are still pristine, but this is be difficult since it is the start of sublimation which generates a coma and makes them discoverable. However, dedicated searches will provide OWL with early discoveries from which will be determined the volatile content of the nuclei, by spectroscopy and from the sublimation temperatures of various ices. During their perihelion passage, OWL will follow on a km scale the detailed morphology of gas-dust jets, right down to the nuclear surface. This will reveal if the dust is released directly from the nucleus or from the gradual destruction of larger grains some distance from the surface.

3. The stars themselves

3.1 The formation of stars and planetary systems

3.1.1 Introduction: a wealth of questions.

Numerous observations have by now fleshed out the original outline scenario (Shu et al. 1987) of how isolated low-mass stars form. A vast range of questions nevertheless remain unanswered, however.

In outline, we believe the process includes the following stages:

1. *Condensations grow in molecular clouds.* See 3.1.2, below.
2. *An "inside-out" collapse commences* when the density of a condensation reaches some critical value. This process proceeds on a time scale governed by the local sound speed.
3. *A protostar forms.* This is surrounded by an accretion disk, while both are deeply embedded within an envelope of infalling dust and gas.
4. *The bipolar outflows* are amongst the dramatic phenomena occuring during this phase. These have a separate and important impact on the surrounding cloud material on scales of several parsecs.
5. With the passage of time *the inflowing material falls preferentially onto the disk rather than the star.*
6. In the last stages *the disk may be fully dispersed* by an energetic outflow *or may coagulate, at least in part, into planets.*

For the task of exploring the vast range of physical conditions that occur during star formation, high resolution imaging and spectroscopy are essential in a number of areas. Spatially resolving the core inflow and accretion disk, and establishing the density, temperature and dynamical structures of these features, are essential to providing constraints on models of the physics of these structures.

Several major questions await answers: How does the jet outflow originate from the accretion disk? How does it start? What keeps it stable?

We need images and spectra of the jet-formation region with resolution high enough to resolve both the different spatial regions and the gas kinematics involved. OWL will give us these.

Planet formation, too, is a subset of this topic which abounds with unanswered questions which can only be answered by observations at high spatial and spectral resolution.

1. What fraction of the disks are forming planets?
2. At what stage in the accretion process are planets formed?
3. How long do they take to form?
4. What determines their masses?
5. Is *our* solar system "typical", *i.e* formed under "typical" considtions?, and by corollorary,

6. What density, temperature and kinematic structure characterise those disks in which they form?

Below we outline how OWL will help answer some of these questions.

3.1.2 The birthplaces: The fine structure, kinematics and chemistry of molecular clouds

Stars and planets form within dark molecular clouds. However, despite 30 years of study, little is understood about the internal structure of these clouds and consequently the initial conditions that give rise to star and planet formation. This is largely due to the fact that molecular clouds are primarily composed of molecular hydrogen, which is virtually inaccessible to direct observation. Most of what we learned until today was derived from observations of trace H_2 surrogates, namely those rare molecules with sufficient dipole moment to be detected by radio spectroscopic techniques and interstellar dust, whose thermal emission can be detected by radio continuum techniques. Nevertheless, several poorly constrained effects inherent in these techniques make the construction of an unambiguous picture of the physical structure of these objects a very difficult task, and the correct description of the way Nature chooses to form stars an elusive dream.

OWL, operating at NIR wavelengths, will bring the end of the "dark cloud" era. Virtually all molecular clouds will become transparent at the sensitivity of an ELT at NIR wavelengths, except for the densest cores. A careful analysis of the NIR light seen through a molecular cloud will provide direct measurements of the dust column density toward background light, coming either from stars or galaxies. Such measurements are free from the complications that plague molecular line or dust-emission data and will enable exquisitely detailed maps of cloud structure to be constructed. More quantitatively, there are around 10^5 stars down to $K \sim 28$ arcmin^{-2} towards the plane of the Milky Way, or around 300 stars arcsec^{-2}, which will allow the construction of maps with resolutions on the order of $0.''1$, which translates to about 10 AU linear resolution in the nearest star forming regions, and with an impressive dynamical range of $0 \leq A_v \leq 300$ mag!. Since one should expect $\sim$1 galaxy arcsec^{-2} the worst possible resolution of an OWL column density map should be of the order of a couple of arcsec.

The resolution of an OWL column density map of a molecular cloud compares well to the resolution to be achieved by ALMA. But the FOV covered (say around 1 arcmin^{-2}) in one OWL frame) is far larger than the ALMA FOV. Nevertheless the two facilities are highly complementary, as is the submillimetre camera SCOWL proposed elsewhere. A comparison of molecular-line maps and dust emission maps with the OWL NIR column density map, will allow the study of the chemistry of the star formation process and interstellar grain properties (e.g., grain emissivity properties, grain growth) on Sub-Solar System size scales. The expected dynamical range and resolution will allow this type of study from the quiescent molecular material phase, through the pre-stellar and protostellar phase, ending on the dispersion of the parental molecular material by the newly formed star.

The immense sensitivity of OWL for spectroscopy in the near-IR and especially in the mid-IR will allow detailed studies of the chemical and dynamic properties of the quiescent cloud by absorption line spectroscopy at high resolutions (R$\sim$100,000). This is possible because OWL will be able to secure spectra of *numerous, background* stars rather than the embedded objects which current facilities are in almost every case forced to use as illumination sources for such experiments. These imbedded objects usually have their own strong influence on the surrounding cloud, so we have little knowledge of its properties away from such centres of activity. OWL will provide numerous sightlines through undisturbed, pristine molecular material.

3.1.2: The accessible laboratories and OWL's capabilities.

Inescapable limits are set on our ability to examine the star formation process in detail. These arise from the distances from the Sun of the nearest locations where the various phenomena are to be observed. The closest molecular complexes where low-mass star formation is currently occurring are the ρ Ophiuchus, Taurus and Chamaeleon complexes, all $\sim$150 pc away, while the nearest centre of high-mass (OB) star formation is in Orion, 500 pc away. We are fortunate to have nearer to hand, only 50 pc away, the TW Hydrae association of objects which offers a sample of pre-main-sequence T Tauri stars, in the late (planet-forming?) stages of their initial disc evolution.

At $\lambda = 1$ to 5 μm in the near-IR OWL will offfer spatial resolutions of 2 to 10 mas. The shorter wavelengths in this range will include emission from the hottest dust and gas, *i.e.* from stellar photospheres, shocked and otherwise heated material, as well as scattered light from the protostars themselves. Also visible will be hot gas in face-on or low-extinction circumstellar discs. At 2 - 2.5 μm molecular hydrogen (H_2) and 1st overtone CO lines are available as diagnostics; in the 3 to 4 μm windows the PAH and other organic emission and absorption features and hydrogen Brackett α are available. In the 5μm M window the CO fundamental lines offer powerful diagnostics with good ability to penetrate dust (greatly helped by OWL's enormous light-gathering power: see section 3.1.2).

The Mid-IR bands offer spatial resolution $\sim$20 mas around 10 μm, declining to $\sim$ 40 mas at $\sim$20μm, and will show inner warm regions of circumstellar disks at temperatures around $\sim$100-500K, expected to be generated by radiative heating of dust within few AU of central star. A number of emission and absorption features are also available in this wavelength range, in particular the silicate features at 9.7 μm, and several potentially valuable diagnostic features in the pure-rotation lines of H_2. The 28 μm 0-0 S(0) line is not accessible, but the 17.0 μm 0-0 S(1) line has already been detected from the ground, and from space from the circumstellar disc of the YSO binary GG Tau (Thi *et al.* 1999, ApJ, 521, L63). This line arises in material at a few 100s K and is a particularly useful potential tracer of features in the H_2-rich circumstellar discs.

It should be noted that ALMA (resolution also $\sim$20 milliarcsec), will play a highly complementary role, being well suited to observing relatively high column densities of much cooler 20-100K gas and dust.

The resolutions offered by OWL at a range of wavelengths in the above-mentioned nearby targets are summarised in the table.

Distance (pc)	Target	Resolution (**res. el. per AU**/*AU per res. el.*) 1μm	2μm	5μm	10μm	17μm	350μm
10		**50**	**25**	**10**	**5**	**3**	*7*
50	TW Hya assn.	**10**	**5**	**2**	**1**	*2*	*35*
150	ρOph, Tau, Cham	**3.3**	**1.7**	*1.5*	*3*	*6*	*100*
500	Orion	**1**	*2*	*5*	*10*	*17*	*350*

3.1.4 Inner discs

Currently the models of what is *actually* happening in the central 30 AU are almost completely based on theory and guesswork; they are desperately in need sound observational data.

OWL will be well able to resolve structures in this inner disc region in the near-IR, offering sub-AU performance to 10μm in the TW Hya association and at 3-4μm out to the ρ Oph complex.

Simple imaging of discs at high resolution offers an important start on these investigations. Especially in edge-wise systems, detailed modelling and matches to observed isophotes is expected to yield strong indications of the presence and nature of imbedded planetary bodies.

Variations in molecular abundances with radial position in circumstellar discs will be compared with those seen in comets in our Solar System. This will offer one answer to the question posed above: are we a "typical" system or not?

Gaps in discs are expected to be associated with planet formation, representing ranges of radii within which the acccreting planet has swept up most of the disc material. Such gaps have been inferred in a number of systems (REFERENCE? EXAMPLES?) from observations of deficient wavelengths in spectral energy distributions, but these inferences are notoriously model dependant.

A successful demonstration of the existence of an annular gap is a particularly desirable outcome. Such a feature is a near-certain indicator of the presence of a protoplanet and the *width* of the gap, if it can be measured or inferred, is a direct measure of the *mass* of the planet.

It has been pointed out (K.Olsen, personal communication) that this measurement may be possible by searching for signs of shocked emission where supersonic flow is engendered by the planet's gravitational perturbation of the disc gas at the edges of the gap. Emission from the shocked locations, on either side of the gap, should be detectable in the 17.03 μm line of H_2. Even if the gap is unresolved, the velocity shear across it will impose a clear signature on the observed emission line profile.

An especially interesting possibility is open only to OWL: following the emission locus as it orbits around the star (a 5 AU orbital radius is about 2.5 resolution elements at the TW Hya complex and about 1 at ρ Oph).

The is some prospect for OWL of direct spatial resoution of the emission loci on either side of the gap: a Jupiter-mass planet is expected to produce a $\sim$ 1 AU gap at 5 AU radius; this is $\sim$2 resolution elements wide at 2 μm at the distance of the ρ Oph, Taurus and Chamaeleon complexes, so that if significant emission in the 1-0 S(1) line at 2.12μm results, it should be spatially resolvable. However the high excitation temperatures required by the NIR H_2 lines make this a speculative possibility: more promising is the prospect of resolving the emission locations in the intermediate lines of the pure-rotational series: the 0-0 S(3) line at 9.66 μm, in particular, should be adequately strong and should should be resolvable in stars of the TW Hya association.

Direct detection, and possibly, resolution, of planetary gaps should also be possible using HI Brackett α line emission from the diluted gas in the gap itself, which will be well resolved

($\sim$3 resolution elements) for Jovian planets in circumstellar discs of the members of the TW Hya association. Indeed a face-on multi-planet system might resemble a bulls-eye in the light of this emission line.

Aside from direct resolution of gaps in these diagnostic lines, critical new insights into the structure of the inner (planet-forming) circumstellar discs will be available. The 17.03 μm H_2 line will trace shocked structure to $\sim$ 2 AU resolution at TW Hya, while Brackett α offers $\sim$ 4 AU resolution in Orion.

Aside from phenomena associated with planet formation, other important phenomena are concentrated in the previously-inaccessible inner parts of the disc. The region within 10 AU of a young star is likely to be the source of bipolar outflows, and is also the region where accretion may generate significant luminosity through shocks, at least in the younger discs (see above, 3.1.1).

The dynamics in this region are dominated by rotation, accretion and outflow. However, the motions are likely to be complicated by convection (above the disc plane), non-axisymmetric features such as spiral density waves, and time-dependent highly-clumpy accretion. This region is also around the so-called "snow line", where water-ice will rapidly sublime, significantly affecting the chemical abundances and dust composition. Photoionisation is also likely to be important for molecular gas depletion in the faces of the disc exposed to the star. Dust coagulation - preferentially in the densest parts of the disc plane - may substantially alter the visual extinction and hence the temperature.

All these effects are intertwined, and need to be addressed before any meaningful star/planet formation theories can be usefully tested.

3.1.5 Embedded YSOs: Mid-IR targets

Class I-II young stellar objects. These represent the younger, more embedded stages, of the star-formation process. The inner few AU of the disc will, in most cases, be highly extinguished in the optical, so these objects are not accessible to milliarcsec-resolution optical observations. However extiction will be 10x lower in the mid-IR, while the temperature in the interesting inner few AU means that emission will peak in the mid-IR. For these objects, a high priority would be mid-IR diffraction-limited resolution with OWL telescope ($\sim$3 AU in the closest SF regions).

Observations at high spectral, as well as spatial, resolution are needed to understand the disc dynamics; velocity resolutions of a few km/s (R $\sim$100,000) are desirable. Such resolutions will also help to dilute the bright continuum against which spectral features must be observed. As before, important targets include the pure rotational H_2 line at 17.03 μm and the CO fundamental lines at $4.6\mu m$. Other species will also assist in understanding the physical conditions in the inner nebula

These observations can only be contemplated given the essential combination of high spatial resolution and light-gathering power sufficient to allow high spectral resolution achievable only with an OWL-sized facility.

3.1.6 Outflow dynamics and moving shadows.

Time-lapse imaging will be a key new facility to help disentangle outflows, shocks and the disc dynamics in YSOs - it may no longer be useful to publish single images of a flow, as only a movie will be meaningful. An early example of the sort of results that might be achievable are the 4-frame proper motions of the jet clumps and the dark shadow on the disc in HH30, taken over 10 years with the HST (web ref).

Optical and infrared lines of shocked gas would be used. Typical outflow velocities of 100km/s mean that proper motions of outflow features within one day will be easily measurable for D=150pc with a 100m ELT.

3.2 The lives of massive stars

3.2.1 Introduction

Massive stars are beacons, wreckers and the engines of change within their galactic environments. A major goal in astronomy is to achieve a good understanding of how these stars form, evolve, modify their environments and die explosively. Even with present telescopes, high mass stars are picked out as individuals in galaxies well beyond our local group, while the HII regions that they ionize can be seen out to quite large redshifts. When OB stars more massive than $\sim 8\ M_{\odot}$ explode as supernovae, they dramatically complete the process of deposition of kinetic energy and chemically-enriched matter in the local ISM that begins soon after they formed. Only recently have we begun to notice, through HST-inspired studies of the Orion and other galactic HII regions, that the presence of high mass stars modifies the early evolution of low mass stars in their vicinity. On the other hand we know essentially nothing about how the high-mass stars actually form; we have a poor grasp of how the most massive (and influential) stars evolve and we would like to understand which stars will end their lives as neutron stars and which will form black holes.

The main contribution of an OWL to this endeavour will be (i) the application of its high spatial resolution to Galactic studies, (ii) the possibility to push the study of these objects out to a far richer variety of galactic environments, a long way beyond the local group (see also the section on Stars and Galaxies), (iii) to punch through severe reddening - at NIR wavelengths OWL may peer through A_V of several tens of magnitudes.

3.2.2 The early phase

Hot cores and compact HII regions are the locations within the galaxy identified as the sites containing very young luminous stars ($\lesssim 10^5$ years old). These are spread throughout the Galaxy's spiral arms but are rarely seen at distances closer than 1 kpc (existing radio catalogues list distances ranging typically from a few up to 15 kpc). There is already a debate about whether massive stars can form through disk accretion as do low mass stars, or whether merging has to be the way. Linked to this question is the problem of the impressive outflows from these young stars that have been signalled via CO velocity-channel maps and velocity-broadened IR line emission. A further issue to be faced is what rôle magnetic processes may have in high mass star formation – a strong hint that this must be on the agenda is the peculiar behaviour displayed by θ^1 Ori C that suggests this early O star is an oblique magnetic rotator!

OWL and ALMA will produce complementary scientific results. OWL will build on ALMA's insights into the dust and molecular gas close to young massive stars by exploring the ionized gas, interior to this, at mainly IR wavelengths, on finer angular scales than ever achievable before.

Radio observations of free-free emission from ultra-compact HII regions (UCHIIs) imply length scales ranging between ~ 100 AU (resolved in the radio in one or two nearby examples) through to 1000 AU or so. Existing 4- and 8-metre class telescopes are determining the stellar content of such regions in the galaxy by near-IR imaging (Henning *et al.*REFREF in A&A) and spectroscopy.

For the next step we need narrow-band imaging and spectroscopic studies of the immediate environments of the exciting sources of UCHIIs, on scales down to 10 or even 1 AU, *the last decade of the NIR resolution of OWL in Orion, the nearest site of this activity.* Such observations will determine for the first time the real incidence of multiplicity, a crucial datum, given that high mass stars appear particularly prone to multiplicity and are suspected of being assembled by mergers. OWL will resolve disks, if present, despite intervening extinction. OWL's diffraction limit at 10μm is 10 AU at Orion; again, significantly worse resolution will vitiate such observations, so *this is an observation which can only be undertaken by OWL.*

Outflows will be easier targets. OWL will use emission lines to study the wind-wind, wind-cloud and wind-ISM interactions, and the associated photo-evaporative processes which appear to dominate the evolution of lower-mass stars and discs (*c.f.* the Orion 'proplyds').

OWL is probably our only hope of penetrating at high spatial resolution through the dust which shrouds the hearts of even the nearest molecular clouds to 'see the star' at the earlier stages that can currently only be studied at sub-mm wavelengths. At these last wavelengths too (q.v.), OWL's huge aperture and excellent optical quality will enable related key studies to proceed with adequate resolution *and field of view* for the first time.

OWL will do for massive star formation that which fully AO-enabled 8-metre telescopes will shortly do for older, less-embedded, T Tau stars at typically under a tenth the distance.

3.2.3 The mature phase: outflows

The trajectories in the HR diagram of the most massive stars ($M \gtrsim 50 M_{\odot}$) remain very poorly known.

It is known that the most massive stars can lose most of their mass before exploding as supernovae. Such stars are the fastest-evolving and, in their evolved and exposed phases, the brightest, of all. They are the first sources of enrichment in metal-poor environments. Particularly fine, and still distinctly mysterious, examples of these 'top-end-of-IMF' objects are η Car, P Cygni and the Pistol Nebula exciting star in the galactic centre.

Key clues to the evolutionary status of such a star are its surface chemical composition and those of its outflow and ejecta. To determine these it is necessary to understand the physics of the winds and relic nebulae. In deeply-obscured cases such as η Carinae, this understanding is needed to identify basic attributes of the star and its circumstellar environment: η Car is imbedded in a dramatic bipolar nebula (beautifully imaged by HST) and is suspected to be double or even a triple system – but we have no idea what really lies within nor what it means when the system has an 'outburst'. OWL will monitor this and similar objects by narrow-band imaging and 3D spectroscopy to resolve the smallest scales and follow fine structure as it dynamically evolves and propogates outward. By the time OWL is built, numerical models of these phenomena be hugely advanced, and *OWL's observations will provide the critical tests for these models.*

OWL will resolve circumstellar structures at η Car down to 10 AU in the near- and thermal IR. This is $\sim$50 R(star), so OWL will certainly reveal if an ionised disc is present and has a high likelihood of determining whether the star is in fact multiple. In general for studies like this high spectral resolution and sensitivity are needed to reveal the kinematic details of the outflows, which, because of the low surface gravities of these distended extreme supergiant stars, tend to be very slow.

Monitoring will be important: shells may be expected to become observable within a few weeks of ejection, and in more compact objects within a few days. Spectropolarimetry is expected to prove critical for understanding these huge and complex systems, and here ahgain the great collecting area and high resolution of OWL will make it by far the most powerful available facility for carrying out these photon-starved observations.

3.2.4 Normal and peculiar stars: studies of resolved stellar surfaces

The superb angular resolution obtained with OWL in the optical (1 mas in V for a 100-m baseline) enables to directly map the surface of some types of nearby stars. The "Catalogue of Apparent Diameters and Absolute Radii of Stars" by Fracassini *et al.* lists on the order of 100 stars with diameters of 10 milliarcsec or greater. An ELT with resolution 1 mas will thus produce at least 100-pixel-images of the *photospheres* of each of these stars, which include the nearest red giants, first ascent red giant branch (RGB) stars and asymptotic giant branch (AGB) stars around 100 pc, and red supergiants around 1 kpc distance. Solar-type main sequence stars may be (marginally) resolved up to a distance of about 10 pc.

Thus it will be possible to directly see structure in the surface temperature (and/or abundance pattern), for instance due to stellar spots related to emerging magnetic flux tubes or due to (super-)convection cells in the mantles of red giants. Magnetic fields may be directly mapped by means of integral field spectro-polarimetry from circular polarization (at typically an 0.1 percent level) in the wings of photospheric absorption lines. Narrowband imaging or integral field spectroscopy will reveal chromospheric activity, for instance in the form of H-alpha filaments and protuberances. Mapping and monitoring the radial velocity pattern across the stellar surface will reveal differential rotation, inclination of the rotational axis, and/or (non-)radial pulsation of the surface. Because of the brightness of the sources and the modest contrast (structures that deviate at a 1 percent level compared to neighbouring stellar surface), a Strehl of near 90 percent is desirable.

Seeing the surfaces of nearby solar-type stars and red (super)giants will teach us a great deal about the structure and dynamics of stellar interiors, which is hitherto hampered by an incomplete understanding of basic physical principles such as turbulence, convection and the generation of large-scale magnetic fields.

Indeed a far larger array of potential targets for detailed spectroscopy are made accessible by the huge collecting area and exquisite resolution of OWL, which, for example will permit spectro-polarimetry at resolutions up to R=100,000 at S/N=100 in exposures of the order of 1 hour down to $V \sim 18$.

3.2.5 The late phase: the mass function of black holes and neutron stars

The best known examples of stellar black holes are those in the so-called low-mass X-ray binaries (LMXBs). These are X-ray transient systems formed by a compact object (either a black hole or a neutron star) and a slightly evolved stellar companion. As a consequence of mass transfer from the secondary, these systems suffer transient outbursts which re-occur, typically, once every several decades. Exploring the properties of these systems requires time resolved spectroscopy to determine radial velocities. If these can be obtained not just for the compact object and its accretion disc, but also – in the IR – for the companion star, the masses of each can be determined.

Many new transients will be detected by X-ray monitoring satellites in the coming decades. While the vast majority will be too distant to be observed by the current generation of ground based telescopes, VLT studies of nearby examples will explore the physics of the accretion disks and the properties of the highly-peculiar secondary stars. Determining the radial velocity curves, which have typical amplitudes of 400 km s^{-1} and orbital periods $\sim$10 h, requires 20 or more spectra with S/N $\geq$10 and resolving power $\sim$1000, distributed around the orbit. A typical LMXB secondary star has $M_V \sim 8$ or $M_H \sim 6$; the tremendous light-gathering power of OWL will allow it to secure suitable spectra in $\lesssim$ 15 minutes out to distance of 50 kpc, permitting LMXB component masses to be determined throughout the galaxy and the Magellanic Clouds. Such a data set will allow the determination of the distribution of masses among black holes and neutron stars and even its dependence on location and the heavy-element abundance of the parent galaxy.

3.2.5 The physics of neutron stars

These have hitherto been studied mainly in radio and X-rays. However, to study the neutron star itself (i.e. not the accretion-flow emission in an X-ray binary), optical, highly time-resolved photometry and spectroscopy of an *isolated* neutron star may be the optimum.

These objects are faint (likely candidates have V >26), and a search for e.g. their nonradial oscillations (predicted periods in the range of milliseconds or 100's of microseconds) obviously require a facility like OWL, and would be quite challenging. About 4h of observing in phase with the pulsar's period would be required to build up a 300-point light curve of a V = 26 pulsar resembling the Crab (30 ms period).

Time-resolved spectrosopy, even at low resolution, would be a substantial challenge even for OWL. Spectra at (say) 300 points around the cycle could be accumulated on a CCD by in phase charge transfer, but even at R $\sim$ 100 many nights would be needed to accumulate a useful result (roughly a week to SNR $\sim$ 5.

Although, at first sight, it could appear that X-ray observations perhaps would be more suitable, their potential is limited by the limited number of X-ray photons that realistically can be collected over such short timescales by foreseen space instruments. A detailed probing of neutron-star interiors would enable a better understanding of baryonic matter and is, of course, of considerable interest also outside astronomy proper. Other neutron-star related observations include the optical counterparts of millisecond pulsars, of relevance for pulsar physics and branches of radio astronomy.

The nature of the galaxy's dark halo

Microlensing events toward the LMC and the bulge of our Galaxy have confirmed the existence of a population of MACHOs (Massive Compact Halo Objects) which may account for a significant fraction of the dark matter in the halo. However the nature of these lensing objects is unknown. Depending on distance, by about a decade after the lensing event OWL will be able to resolve the lens from the lensed star. This will enable investigation of the lensing object by direct imaging and spectroscopy. If the lenses are old (cool) white dwarfs, as claimed, spectroscopic examination will provide an unique opportunity to date and trace back in time the various phases of the Galaxy halo. At 50 Kpc, a 0.5 $M_{\odot}$15 Gyr old DA WD will have $V \sim 32$ ($R - I \sim 0.3$).

Identification of the lenses would permit the determination of their space motions (proper motions of 0.1 mas/y and radial velocities of 200-400 km s^{-1}) and spectroscopic characteristics. This will provide unique information on the very early phases of our Galaxy and also on the physics of such very old degenerate objects.

Halo brown dwarfs, other possible MACHO lenses, can be directly imaged and spectroscopically examined up to distances of order 1 kpc in the galactic halo. At 1 Kpc, a 0.05 $M_{\odot}$old brown dwarf may have J=28 and K=29 (it will be slightly brighter in the R band if they are very metal-poor) according to Burrows *et al.*(1997). Very low resolution spectroscopy R=100 or narrow band filter imaging in the near-IR of the faintest objects will be sufficient to measure the expected distinctive methane and possibly ammonia bands if the MACHOs are indeed brown dwarfs.

OWL will make possible the detection of the more massive brown dwarfs in Galactic globular clusters. Since the magnitude gap between the coolest stars and the most massive brown dwarfs is age dependent, this will provide a new method for globular cluster age dating.