The limits of cosmology: role of the Moon

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1. Introduction

Cosmological advances are proving difficult to maintain with future experiments. There is no detection of dark matter [1], dark energy remains indistinguishable from a cosmological constant [2], and the tensor-to-scalar ratio in the cosmic microwave background fluctuations as a verification of inflation remains elusive and even unreachable for more general, non-Planck scale inflation models [3].

Perhaps we should also be looking elsewhere for potential progress in cosmology. I develop here the case for building lunar telescopes of unprecedented...
size in order to tackle frontier science in cosmology and astrophysics. Two key questions that are central to cosmology and astrophysics can be addressed by lunar megatelescopes. These are: where did we come from, and are we alone in the universe?

The dark ages represent the ultimate frontier that is directly accessible with conventional telescopes. The lunar environment provides a stable platform for the astronomy of the future. Here we can detect the gaseous building blocks that initiated structure formation and probe the 21 cm signals for signs of primordial non-gaussianity, arguably the only robust predictor of generic inflation models [4]. We can build far infrared spectrometers capable of probing the inevitable energy input associated with fluctuation growth from the first years of the universe [5]. We can build 100 m class telescopes, and consider km-aperture infrared interferometers, to provide imaging capability of exoplanets and of the first stars in the Universe [6]. We can search spectroscopically for biological and even technological signatures from many thousands of rocky core, habitable zone exoplanets [7]. We can build gravitational wave interferometers with 100 km baselines that would sample a frequency space band corresponding to a black hole mass regime inaccessible from the Earth or even in space [8]. All of these goals can be uniquely advanced with lunar telescopes.

The first challenge to be addressed with lunar telescopes will most likely be that of the last unexplored frontier in astronomy, the dark ages. Pristine clouds of hydrogen are building blocks of the future but also direct witnesses of the past. Very low frequency radio astronomy is uniquely able to tune into their testimony about the beginning of creation. These early clouds have spin temperatures controlled by atom collisions and are colder than the cosmic microwave background when we observe them after recombination. This is before any stars, galaxies or quasars have formed at very high redshift and generated Lyman alpha photons whose hydrogen excitations would have modified the spin temperature. 21 cm line mapping and tomography at frequencies of 10–50 MHz enables access to previously inaccessible parameter space, sampling a large number of independent modes describing primordial density fluctuations (figure 1).

Critical for such advances is access to small scales $k \sim 10 \text{Mpc}^{-1}$. These may be feasible on a lunar site and with adequate frequency resolution, as described in these proceedings [10]. A lunar platform promises to open a new window on the properties of the early Universe and complement

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**Figure 1.** The scope of different cosmological probes for accessing large numbers of modes [9]. In grey (top) is the TT angular power spectrum in units of $\mu K^2$ divided by a factor of 1000 to be visually comparable to SDSS and 21 cm. Multipoles are roughly mapped to wavenumbers by $\ell = 14,000 \text{k/Mpc}$. In green (second from top) is the dimensionless 3d matter power spectrum computed with CAMB at redshift 1, to which large-scale structure probes such as LSST and EUCLID will be sensitive on scales between $k \sim 0.001$ and $0.1 \text{Mpc}^{-1}$, up to around redshift 2.5. In blue (lowest) is the 3d 21 cm power spectrum in units of $\mu K^2$ at redshift 27, which is the highest redshift accessible from ground-based experiments such as HERA and SKA. In red (third from top) is the 3d 21 cm power spectrum in units of $\mu K^2$ at redshift 50, which would be accessible from the far side of the Moon. (Online version in colour.)
both future (e.g. LiteBIRD/CMB-S4) CMB temperature and polarization signals, and large-scale structure studies with next-generation telescopes on the ground (e.g. SKA/LSST) and in space (e.g. JWST/EUCLID/NGRST), as well as open new reaches in habitable exoplanet yields.

2. Inflation

The non-gaussianity parameter $f_{NL}$ is robustly predicted in single-field inflation, and is generic to multifield inflation, albeit potentially very small. Because of the stringent Planck limits in the $r$–$n_s$ plane [11], where $n_s$ is the scalar spectral index, viable inflationary models today mostly have low tensor-to-scalar ratio $r$. This means that CMB polarization experiments need exquisite sensitivity at the nanoK level compared to the current $\sim \mu K$ limit, wide sky coverage to combat cosmic variance, and broad spectral resolution to eliminate foregrounds, in order to qualitatively improve our understanding of inflation.

Single-field slow roll inflationary potentials which reproduce the measured spectral tilt generally predict $r \gtrsim 0.0001$ and motivate future experimental searches. However, these inflationary models are non-generic, and there is no guaranteed prediction of $r$ [12]. If inflation occurred at an energy much below $m_{inf} \sim 10^{15}$ GeV, then any primordial inflation-induced tensor mode is of strength $r \propto (m_{inf}/m_{pl})$. The tensor-to-scalar ratio is likely to be immeasurably small in many inflationary models [13], with indeed an effective limit of $r \gtrsim 10^{-6}$ being required to avoid confusion with the primordial inflationary tensor signal induced by second-order scalar-induced B modes [14].

Primordial non-Gaussianity, reviewed here [15], provides a robust but challenging complementary probe of inflation. The gauge-invariant Newtonian potential $\phi_g$ is Gaussian but has higher-order correction terms $\phi = \phi_g + f_{NL}\phi_g^2$ that define the density fluctuation three-point function as a direct measure of local non-Gaussianity.

Even the simplest single-field inflationary models predict small but non-zero deviations from Gaussianity, while many multi-field inflation models are expected to have $f_{NL} \sim 1$ and many even predict features in $f_{NL}$. The errors bars on $f_{NL}$ scale with the inverse of the square root of the number of independent modes. The limited number of modes in the CMB ($N \sim 10^6$) and in large-scale galaxy surveys ($N \sim 10^8$) strongly motivates the exploration of 21 cm dark ages cosmology at $z = 25–75$ (20–60 MHz), where approximately up to $10^{12}$ modes can be explored, at least in principle. Attainment of a robust limit on (or detection of) primordial non-Gaussianity would provide the ultimate probe of generic inflation.

The first quantitative estimate of the minimum value of primordial non-Gaussianity was given for single-field slow roll inflation [16], with the result that the three-point functions are determined completely by the tilt of the spectrum of the two-point functions for the scalar mode, enabling the primordial non-Gaussianity to be expressed in terms of the spectral tilt as $f_{NL} = -(5/12)(n_s - 1)$. While $f_{NL}$ may be much larger in multifield inflation [17], in single-field inflation, however, there remains at least a minimal effect of the Maldacena conjecture for local non-Gaussianity [18]. One can thereby test inflation, primordial non-Gaussianity being a guaranteed signal, and even its quantum origin may be revealed [19,20].

3. CMB spectral distortions

Following the pioneering observations with COBE/FIRAS in the early 1990s, the theoretical foundation of spectral distortions has seen major advances in recent years, highlighting the immense potential of this emerging field to probe the thermal history of the Universe from when it was a few months old until today. The sky-averaged CMB spectrum is known to be extremely close to a perfect blackbody at a temperature $T_0 = 2.7255 \pm 0.0006$ K, with possible distortions limited to parts in $10^5$.

Spectral distortions from the predicted blackbody spectrum of the cosmic microwave background, the fossil radiation from the Big Bang, are an important tool for understanding the physics of recombination and reionization, the origin of structure, and the origin of the
CMB itself. The required high precision measurements of the CMB energy spectrum would open a new window into the physics of the early Universe, constraining cosmological models and fundamental physics in ways not possible using other techniques, most notably by searching for blackbody spectral distortions.

This new horizon for cosmology urgently merits serious exploration in part as a consequence of the uncertain prospects for detecting a primordial B-mode signal from inflation. It is especially relevant to therefore consider complementary approaches that are capable of yielding unique information on the primordial universe, directly probing unprecedentedly early epochs back to the epoch when the cosmic blackbody radiation originated or even all the way back to the end of inflation. This goal can only come from the diffuse cosmological backgrounds of cosmological neutrinos, gravitational waves or relic photons. Of these, neutrino detection, while possible in principal, remains highly futuristic [22], and measuring spectral distortions would be a vastly more remote goal. Direct detection of a stochastic gravitational wave background is plagued by instrumental noise [23], and predicted spectral distortions of the relic photon background radiation are seen against immense far infrared foregrounds. We can still be optimistic about feasibility, in large part because we have been here before in terms of overcoming foregrounds. The unprecedented limits on infinitesimal deviations from a blackbody reported by the COBE FIRAS experiment and the further refinements projected with CMB-S4 and proposed space experiments highlight a new pathway for future exploration.

There are many papers on generating spectral distortions in the early universe: for example, by decaying dark matter, evaporating primordial black holes, and even more exotic phenomenology. However, it is frustrating to realize that there are no guaranteed cosmological signals for such exotica. Hence exploration of the unknown becomes difficult to justify when in competition with missions that advertise guaranteed science goals. This is despite the fact that the historical record demonstrates that such a new horizon approach is an invaluable part of humanity’s drive to explore the universe with the prospect of vast but unforeseeable returns. In fact by being sufficiently ambitious, guaranteed science central to cosmology is achievable via a CMB spectral distortion experiment.

More specifically, spectral distortions provide a unique window that exposes the physics of the very early universe, and provide a fundamental test of the Big Bang theory, if one can overcome the various foregrounds. Sources of spectral distortion arise in the pre-recombination and post-recombination epochs where spectral distortions emerge as a combination [24] of late epoch \( y \)-distortions [25] and early epoch \( \mu \)-distortions [26] in the standard \( \Lambda \)CDM model, along with a transition phase [27].

The former measures energy injection in the radiation-dominated era, after the first months, when thermalization into the cosmic blackbody radiation is no longer efficient. There are inevitable spectral distortions that arise from energy injection via damping of adiabatic baryon fluctuations if cold dark matter is the dominant form of dark matter [28].

Cold dark matter generically describes many types of dark matter, spanning bosonic axions of mass microelectron volts, motivated by QCD and resolution of the strong CP problem, to weakly interacting massive fermions (WIMPs), motivated by supersymmetry, of mass up to 100 TeV and yielding the observed dark matter fraction for typical weak cross-sections, and even to ultralight axions, motivated (controversially) by the prevalence of dwarf galaxy cores.

Unitarity arguments limit the WIMP mass: at higher masses, the cross-section is found to be too low and WIMPs are overproduced. However, refined estimates allow a window at the few TeV mass scale where massive particles are well-motivated candidates for dark matter that have not so far been detected despite intensive searches [29]. Verifying the \( \Lambda \)CDM model is therefore of the highest importance. Given the vagaries of dark matter direct or indirect detection searches, measurement of the early universe CMB spectral distortions at the dwarf galaxy precursor scale may provide a unique pathway towards this goal.

Dwarf galaxies are a key frontier for dark matter cosmology. New generations of telescopes and surveys allow their detection at unprecedented surface brightnesses and distances. They provide unique laboratories for harbouring dark matter largely uncontaminated by the presence
of stars. Yet their numbers are largely unknown, presenting an important diagnostic for cosmology, one that indeed has motivated many speculations about the role of astroparticle physics in controlling their abundance and other properties.

More information on their abundance, especially in terms of the primordial power spectrum, would be invaluable. This issue can be resolved via $\mu$-type spectral distortions. One can probe the abundance of dwarf galaxy precursor fluctuations by probing the primordial fluctuation spectrum on scales that are only accessible to spectral distortions. Direct measurements of CMB temperature fluctuations are damped away on these scales. But the damping comes with a price: energy generation, visible uniquely via $\mu$ spectral distortions.

However only one number is measured for energy input in the $\mu$ era, and one cannot distinguish between the various competing and hypothetical energy inputs. The only guaranteed return is that of testing the CDM prediction of adiabatic fluctuation damping, which generates dissipation on dwarf galaxy scales in the radiation-dominated era, after the epoch of thermalization at approximately $10^6$ s or $z \sim 10^7$ [30]. Detection of the resulting $\mu$-distortions would be a major cosmological result but requires a sensitivity of $10^{-9}$, some four orders of magnitude improvement on FIRAS.

Detection of the damping of dwarf galaxy fluctuations would allow a unique glimpse of their cumulative power and test one of the most important predictions of the cold dark matter hypothesis, in precisely the mass range available to $\mu$-type spectral distortions. These probe wavenumbers spanning 50–500 Mpc$^{-1}$ corresponding to mass scales $10^7$–$10^4$ M$_{\odot}$ and generated via the baryon damping power at $10^4 \lesssim z \lesssim 10^7$, on otherwise unobservable dwarf galaxy scales. Baryon damping has been measured via the CMB acoustic oscillations on galaxy cluster scales, and it would be a fundamental extension and confirmation of the standard cosmological model to detect such effects emerging down to dwarf galaxy scales. This is important for distinguishing CDM from such rivals as [31] WDM (warm dark matter), SIDM (self-interacting dark matter), FDM (fuzzy or ultralight dark matter) and other models with power spectrum cut-offs.

However, one can do even more. Going one order of magnitude further in sensitivity [32] would enable detection of hydrogen and helium recombination lines at $z \sim 10^3 – 10^4$, including the Paschen, Balmer and Lyman lines, and provide the deepest images ever attainable of the emerging universe. Detection of the recombination lines in the energy spectrum of the cosmic microwave background would be a clean probe of the first atoms formed in the Universe and a ‘holy grail’ for understanding the physics of the early Universe. The imprints of the recombination lines cause tiny deviations in the blackbody spectrum of the CMB with highly predictable features determined by atomic physics and the cosmic constituents of the Universe (figure 2).

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**Figure 2.** Spectral distortions versus frequency, demonstrating the infrared foregrounds, the standard and relativistic $y$ and $\mu$ spectral distortions and the hydrogen and helium recombination lines. Also shown is the proposed PIXIE sensitivity and the target sensitivity needed for a guaranteed minimal science return. Adapted from [33]. (Online version in colour.)
The (re)combination spectral lines of hydrogen provide unique spectral distortions produced 380,000 years after the Big Bang. We currently measure atomic hydrogen directly in absorption against quasars to $z \sim 7.5$ [34]. Most recently, we may have controversially detected redshifted 21 cm absorption of H atoms to $z \sim 17$ in the EDGES experiment. Measuring hydrogen atoms at $z \sim 1000$, long before the first stars formed, would be an unprecedented advance in our confirming the physics of the Big Bang.

The most remarkable goal would be the first direct measure of the primordial helium abundance $Y_p$. Planck does this indirectly, but $Y_p$ is degenerate with the number of relativistic species at BBN at roughly the 20% level. The (re)combination spectral lines of helium take us back to an epoch long before any helium-synthesizing stars had formed, thereby bypassing the major uncertainty in direct measurements of $Y_p$. We can measure helium recombination lines back to $z \sim 2000$ for He$^+$ and 6000 for He$^{++}$. Detection is inevitable with enough sensitivity and would confirm the production of helium long before any stars had formed, and probe the first atoms in the universe some 20,000–100,000 years after the Big Bang.

One needs a far infrared space telescope with an interferometer dedicated to spectral distortions and a large improvement on PIXIE sensitivity, of order 10–100. The proposed but unfunded PIXIE is a dual input Martin–Puplett interferometer with two entrances, one looking at a reference blackbody and one focal plane detector looking at the sky with the mirror of a single 55 cm diameter telescope. PIXIE was rejected twice by the NASA MIDEX program, in part because it lacked the sensitivity for a definitive detection of CMB spectral distortions at the predicted level of $\mu \sim 10^{-9}$.

The advantage of a lunar platform in a dark crater would allow construction of an enhanced PIXIE, to enable imaging on say degree angular scales at the desired sensitivity by increasing the number of focal plane detectors with a larger telescope, reduced bandwidth and with an external reference blackbody. All of these design enhancements would at least guarantee the CDM-predicted $\mu$-distortion detection [35] and open the way to achieving even more sensitive measurements.

4. Dark matter

The lack of success in identifying a particle dark matter candidate generated in beyond-the-standard-model scenarios has motivated exploration of dark matter that builds on known physics in the form of primordial black holes. The arguments for such a form of dark matter were boosted by the early LIGO results of anomalous numbers of massive black hole candidates, although it is now generally accepted that astrophysical mechanisms can account for current LIGO detections and that theoretical estimates of primordial black hole mergers in the mass range 1–100 M$_\odot$ can most plausibly account for $f_{\text{PBH}}$ of order 1% of the dark matter [36]. All of the dark matter in stellar mass PBHs can even be accommodated according to one recent estimate of the predicted LIGO/Virgo merger rate [37]. Recent gravitational wave events in the mass gaps where canonical black holes cannot form (2–5 and 50–120 M$_\odot$ may controversially lend credence to PBH mergers, although astrophysical mechanisms are also possible for these rare events.

The strongest observational constraints come from microlensing searches, which actually constrain $f_{\text{PBH}} \lesssim 0.2$ [38] (approximately) below 10M$_\odot$. Complementary, although less stringent, dynamical limits from ultradiffuse galaxies constrain PBHs in the range 1–100 M$_\odot$ from providing all of the dark matter [39]. There are important implications for dwarf galaxies, the latest high resolution simulations allowing $f_{\text{PBH}} \sim 0.01$ and $M_{\text{pbh}} \sim 25$–1000 M$_\odot$ to simultaneously account for both ultradiffuse dark matter profile diversity and dark matter cores in faint dwarfs [40].

As for more massive PBHs, accretion is argued to result in strong constraints from CMB temperature and polarization signatures [41]. The resulting limits eliminate any significant contribution to the DM density by PBHs in the range $M_{\text{BH}} \gtrsim 100$ M$_\odot$, and even stronger limits are claimed [42]. Accretion onto the PBHs during the epoch of matter domination also results in heating of the IGM, and generates Compton $y$-distortions of the CMB spectrum that are currently unobservable.
However Bondi–Hoyle–Lyttleton accretion rates are highly uncertain especially in the generic limits of inhomogeneous and anisotropic accretion, by some two orders of magnitude once realistic geometries and inhomogeneities [43] are included. Indeed, accretion may even be dominated by mechanical feedback from BH-driven outflows [44,45].

Rather, attention has shifted to the extended mass window from $10^{-17}$ to $10^{-11}$ M$_\odot$ where asteroid-mass PBHs remain a viable dark matter option. Extended limits are obtained via gravitational microlensing down to lens sizes of the order of the Einstein radius most notably in M31, where the lens are typically giant stars, corresponding to PBH masses $\sim 10^{-10}$ M$_\odot$ [46,47].

Hawking evaporation limits from the diffuse gamma ray background and especially high-energy positron fluxes limit the PBH mass to above $10^{-17}$ gm [48]. Uncertainty about the quantum gravity aspects of smaller black holes means that under certain conditions, such as extremal spin or high charge, Hawking evaporation may be avoided [49]. Moreover only an infinitesimal fraction $(1 + z_{eq})/(1 + z_{pl})$ need be stable and long-lived, where $z_{eq}$ and $z_{pl}$ are the redshifts of matter-radiation equality and the Planck epoch, respectively. This means that even (extremal) Planck mass PBHs provide a possible dark matter solution, consistent with all known constraints [50]. Production requires tuning of initial conditions, but at their production epoch, PBHs are exceedingly rare because the Universe is highly radiation-dominated.

Primordial black holes are the only dark matter candidate that avoids introducing new physics. One needs boosted scale-dependent and possibly non-Gaussian initial conditions, available in many inflationary models, leading to spectral power boosts in the primordial density fluctuation distribution.

Particle dark matter has the likely possibility of annihilation or decay as a potential detection signal. The typically high-energy products include gamma rays as well as high-energy neutrinos, positrons and antiprotons. Identification of a weakly interacting dark matter particle candidate is the holy grail of particle astrophysics. However searches in our galaxy and of nearby dwarf galaxies and galaxy clusters, all known dark matter repositories, have had little success.

The dark ages offer a unique environment for exploring long-lived particle annihilations or decays, the 21 cm signal fluctuations being sensitive to electromagnetic energy injection via precision spin temperature measurements of intergalactic hydrogen clouds at very high redshift. However, the low-frequency terrestrial foregrounds are a severe problem, in the absence of space or lunar projects.

There has been one claim of a global signature due to 21-cm hyperfine absorption of cosmic microwave background photons at $z \sim 17$ or at 78 MHz [51]. If of cosmological origin, the HI spin temperature must be coupled to the kinetic temperature of the ambient hydrogen at this redshift via scattering of Lyman alpha photons emitted by the first massive stars, but the magnitude of the signal is about twice as large as predicted by existing cosmological models [52]. The result has been criticized and awaits independent confirmation [53].

In addition, there is no satisfactory theoretical explanation of the magnitude and line profile of the reported absorption feature, effectively requiring extra cooling of the baryons, either in standard cosmology or via scattering of dark matter particles with baryons [54]. Despite these uncertainties, the sensitivity of the dark ages to the most modest energy injection provides potentially large improvements over the best current limits on exotic physics, in a regime that is likely to be uncontaminated by astrophysical processes.

Another early signal that precedes structure formation arises from the abrupt decline in sound speed of the baryonic matter at last scattering, from $\Delta_{\xi}(1 + z_{LSS})/(1 + z_{eq})^{1/2}c/\sqrt{\Lambda}$ $\sim 30$ km s$^{-1}$ in the fluctuations to approximately 3 km s$^{-1}$ in the ambient baryonic fluid. Here $\Delta_{\xi}(k)^2 = 2.4 \times 10^{-9}$ is the primordial curvature ($\xi$) fluctuation variance per ln$k$. Consequently, baryonic matter fluctuations have a highly supersonic velocity dispersion after recombination. This rapidly dissipates as fluctuations collapse but partially suppresses the growth of matter fluctuations on small scales, modifying the small-scale matter power spectrum at high redshift, and leaves an imprint on baryon acoustic oscillations and the epoch of first galaxy formation [55].

Dark matter models that suppress small-scale power (including sterile neutrino dark matter [56] and self-interacting dark matter [57]) can modify this modulation, allowing a possible test
5. Galaxy and supermassive black hole formation

Intermediate mass black holes in the mass range $10^3$–$10^5 M_\odot$ are possibly required for seeding supermassive black holes (SMBH) especially at high redshift [59]. Eddington-limited accretion fails if one begins with stellar mass seeds $\lesssim 50 M_\odot$. The e-folding timescale for growth, the Salpeter time, is $\epsilon M_{\text{BH}} c^2 / L_{\text{Edd}} = \epsilon \sigma_T T_c / (4 \pi G m_p)$, or $45.10^7 \epsilon$ yr. Here, in a steady state, the Eddington luminosity, $L_{\text{Edd}} = 4 \pi G M_{\text{BH}} m_p c^2 / \sigma_T$, sets the maximum black hole mass in which the radiation pressure gradient balances gravitational force and $\epsilon \sim 0.1$ is the fraction of accreting rest mass that is converted into radiation. The Eddington-limited accretion rate fails to give enough growth e-foldings at high redshift, when the age of the universe is a few hundred million years, to account for the most massive SMBHs. For example at $z = 7$, the age of the Universe was only 700 Myr. The Eddington-limited growth rate is too low to permit formation of SMBH with masses as high as observed at high redshift, approximately $10^{10} M_\odot$.

Super-Eddington accretion offers a possible solution, involving highly anisotropic and/or non-equilibrium accretion, possibly visible via flaring, or the changing-look phenomenon. However the duty cycle is unknown, and any observational evidence for super-Eddington accretion on AGN scales remains sparse [60].

Mergers of IMBH seeds provide an alternative resolution, and associated gravitational wave signals should be detectable with LISA. Gas accretion onto the inferred IMBH seeds during the dark ages would leave a unique signature in the 21 cm signal. Such excess power potentially shows up in the 21 cm autocorrelation function, uniquely probed via very low-frequency 21 cm dark ages astronomy [61,62].

A 21 cm lunar radio array could have the sensitivity to detect their signature and constrain their properties, modifying the standard (LCDM-based) view of the high redshift universe and complementing CMB probes. Poisson fluctuations are detectable in the 21 cm power spectrum if the mass fraction of seed IMBH is approximately as high as $10^{-4}$ (figure 3).

Another and complementary approach to massive black hole science is the following. One could exploit the frequency gap between gravitational waves detectable by LISA (sensitive to IMBH mergers of masses $\gtrsim 10^5 M_\odot$) and LIGO/Virgo/Einstein (sensitive to BH masses $\lesssim 100 M_\odot$) to probe the build-up of massive black holes. Construction of a gravitational wave lunar interferometer that would operate at subHz frequencies over a baseline of around 100 km would enable the range of frequencies that cannot be easily accessed by terrestrial or space-based detectors [63].

6. Exoplanets

We now turn to the exoplanet science capabilities of a very large lunar telescope. Current hopes are pinned on LUVOIR [64], a proposed 10–15 m imaging space telescope with capabilities of observing exoplanet spectra of approximately 50 Earthlike planets. These targets are defined to have rocky cores and be in habitable zones of the host stars. These latter are nearby main sequence stars attainable over the course of a 25 year mission. The total sample size for LUVOIR (15 m) for rocky core exoplanets in habitable zones is taken to be 50, since it is capable of searching only a zone 25 pc distant from the sun with sufficient precision.

Now let’s compare these goals to a lunar version of OWL. OWL was a concept of a 100 m telescope [65] that was abandoned in favour of the 39 m ELT, in part because of engineering constraints that made it unfeasible on any terrestrial site. Such constraints do not apply on the Moon, with lower gravity and no winds, and combined with the huge advantage of no atmosphere such a concept merits reconsideration. It will have many unique applications, for example in cosmology, but it is in enhancing exoplanet yields that size is of paramount importance.
Using the scaling with telescope diameter found in [66] for noise dominated by zodiacal light, $N \propto D^{1.8}$, we find that approximately 1000 planets could be imaged (but not resolved) by a 100 m telescope with sufficient signal to noise. Such a yield is a huge statistical gain over LUVOIR and brings significantly enhanced chances of finding atmospheric biosignatures for exoplanets within a search radius of 250 pc.

The limiting factor, however, may be the image contrast ratio: if an orbital star shade is employed, repositioning times may be long. As opposed to telescopes situated on Earth, the Moon’s atmosphere will not introduce a contrast floor, potentially granting access to habitable zones around sun-like stars as well as M dwarfs.
Figure 5. Inferred values of fraction of planets which attain each successive stage of evolution, assuming optimistically high values of $f_{\text{life}} = 0.5$, $f_{\text{photo}} = 0.4$, $f_{\text{multi}} = 0.7$ and $f_{\text{tech}} = 0.6$. The total sample size for OWL (100 m) is taken to be 1000. Colour coding is red, diagnostics of chemosynthesis; blue, photosynthesis; orange, multicellularity; purple, technology signatures. Adapted from [67]. (Online version in colour.)

Extension to NIR wavelengths would give access to spectral peaks of many chemical species, including water, methane, carbon monoxide and dioxide, and oxygen. Observed together, these have been argued to strongly indicate the presence of life, and would be feasible with a reasonable yield by a 100 m telescope for photon-limited $t \propto d^{-2}$ noise. Additionally, IR excesses indicating the presence of excess planetary heat are prime candidates for technosignatures.

Another way of quantifying the yields of different telescope missions is by the certainty with which we can infer the fraction of planets that have various biosignatures. This is typified by the sequence of planets which possess life, and the fraction of those which have developed photosynthesis, then multicellularity, and finally technology. Any form of life is expected to be accompanied by chemosynthesis, the rearrangement of chemical matter. Chemosynthesis is the minimal requirement, essentially equivalent to the presence of gaseous by-products that are indicative of life, chief among those being methane CH$_4$, as well as water, CO$_2$ and N$_2$.

The next step is photosynthesis, the harvesting of energy from the planet’s host star. This innovation provides a mechanism to harvest the dominant source of free energy on a planet. Molecular oxygen is a signpost, along with ozone, NH and OH. Of course, chlorophyll and the associated red spectral edge are key tracers, especially via scattering-induced polarization of vegetation. A following step in complexity is the evolution of multicellularity as a key prerequisite for intelligent life. Examples might include extremophiles, plant biomass signatures via phased signatures of scattered light. Lastly, the detection of technological civilizations, both on the level of and beyond the level that the Earth has achieved, is a final consideration for the feasibility of discovery signatures in exoplanet atmospheres.

Precise biosignatures corresponding to each of these stages of development can be estimated, but planets with each of these characteristics are expected to be successively rarer. The extent to which we can infer the fraction that attain each biosignature level will be limited by the sample size of the exoplanet yield. This is displayed in figures 4 and 5.

The number of exoplanets that needs to be targeted is debatable. However a field of, say, tens of targets with rocky cores in habitable zones is almost certainly too small to have any reasonable odds for success. Ideally a search basis of a thousand or more such exoplanets would seem to be required for detailed multimessenger spectroscopic follow-up. This only becomes available with the aperture provided by a lunar megatelescope.

A secondary goal of such a telescope would be detection of the first stars in the Universe. These are rare but luminous, and could be visible with enough sensitivity as Population III star clusters [68] or transient phenomena such as supernovae [69], or even as individual very massive stars [70].

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**Figure 5.** Inferred values of fraction of planets which attain each successive stage of evolution, assuming optimistically high values of $f_{\text{life}} = 0.5$, $f_{\text{photo}} = 0.4$, $f_{\text{multi}} = 0.7$ and $f_{\text{tech}} = 0.6$. The total sample size for OWL (100 m) is taken to be 1000. Colour coding is red, diagnostics of chemosynthesis; blue, photosynthesis; orange, multicellularity; purple, technology signatures. Adapted from [67]. (Online version in colour.)
7. Final comments

There are many issues that need to be explored before a lunar telescope can be built. The effects of lunar dust and solar cosmic rays on electrical and mechanical components need to be studied. Data collection and analysis presents a challenge along with deployment of robotic capabilities and risks of human servicing.

While the lunar surface is a natural location for low-frequency radio interferometry, with a stable platform, no ionosphere and far-side shielding from terrestrial interference, the case for infrared and optical telescopes is less obvious. The lack of atmosphere provides a unique space-like advantage, and scaling in size offers prospects for imaging and spectroscopy at unprecedented light gathering power. Another key science goal involves construction of a gravitational wave lunar interferometer that would operate at subHz frequencies filling a gap between terrestrial and space-based detectors. Unique advances in cosmology are feasible with lunar telescopes that will probe our cosmic origins within the first thousands of years after the Big Bang and even as far back as the epoch of inflation.

There is a down side, most notably that of charged dust particles. These could affect IR/optical/UV telescope performance. The Moon is embedded in a tenuous impact-generated dust cloud detected by the Apollo lunar horizon glow [71]. Lunar regolith particles are lofted to heights that depend on electrostatic forces, with dust charge accumulation varying with lunar day/night and solar wind/coronal flaring activity [72]. The lack of direct solar exposure may mitigate dust lofting in dark craters although micrometeorite impacts will generate some surface particle activity.

Finally, I note that the budget needed for lunar telescopes, while overwhelming for stand-alone projects, and hence financially unacceptable, remains only a small fraction of the overall lunar exploration budget. Very large space telescopes as free space observatories can be designed to be extremely competitive with the goals outlined here [73], but are likely to be prohibitively expensive as stand-alone projects.

Just as the Hubble Space Telescope might not have emerged without the space infrastructure developed for the International Space Station and the Space Shuttle, at a cost of order 5% of the total budget, we can be reasonably optimistic that lunar telescopes will have a niche alongside, and as a minor component of, the political priorities that drive human exploration and commercial exploitation of the Moon.

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