Ambitious studies of Earth-like extrasolar planets are outlined in the context of an exploration initiative for a return to the Earth’s Moon. Two mechanisms for linearly polarizing light reflected from Earth-like planets are discussed: 1) Rayleigh-scattering from a planet’s clear atmosphere, and 2) specular reflection from a planet’s ocean. Both have physically simple and predictable polarized phase functions. The exoplanetary diurnal variation of the polarized light reflected from a ocean but not from a land surface has the potential to enable reconstruction of the continental boundaries on an Earth-like extrasolar planet. Digressions on the lunar exploration initiative also are presented.

1. Introduction

For millennia humans have observed the classical planets as unresolved points of light moving on the celestial sphere. Now we are on the verge of seeing extrasolar planets as unresolved, moving points of light. We also are exploiting, or soon will exploit, alternative methods of imaging extrasolar planets, one of which we propose in this paper: sea-surface glints.

Astronomical research and human exploration have a strong historical precedent. The global oceanic explorations of Captain James Cook and others were in large part motivated by the possibility of measuring the scale of the solar system in physical units, e.g. meters, by geometrical triangulation of the silhouette of Venus transiting the Sun as viewed from nearly opposite sides of the Earth during the transit of Venus of 1769 (Maor 2000). Cook’s expedition required the significant resources of the greatest naval power on Earth to sail for nearly 8 months from England to Tahiti. That is, he journeyed as far as was humanly possible in the 18th century in order to attempt to answer a scientific question as old as humankind, “How far is the Sun, and hence by elementary geometry, how far are the other planets?” Although Cook and others were blessed with cloud-free skies on the day of the transit, the scientific objective of his expedition failed due to turbulence in the Earth’s atmosphere. From the long view of history, we do not recall such expeditions’ costs in lives or gold, nor does it matter much that they failed in their scientific objectives. Instead, we revere such expeditions for their power to inspire humans to collectively seek great accomplishments for the good of all humankind.

In this paper, we outline a similar scientific quest to understand humankind’s place in the cosmos: a historically significant and achievable scientific goal for NASA would be to identify oceanic extrasolar planets. This goal is simpler than, and also related to, the goal of former NASA administrator Dan Goldin to image the surfaces of extrasolar planets. If we were to attempt such imagery by diffraction-limited optics, the minuscule angular size of an extrasolar planet would require truly enormous separations between the optical components. However, an indirect imaging technique such as that presented in Section 2 may permit mapping the surfaces of extrasolar planets with telescopes that are well within the capabilities of current human technologies. In Section 3 I provide some context to the lunar exploration initiative and some digressions on possible impacts it may have on society.
2. Glints from the Oceans of Extrasolar Planets

We need not spatially resolve an extrasolar planet in order to determine if it has an atmosphere and an ocean like those of Earth. Instead, we propose to exploit the linear polarization generated by Rayleigh scattering in the planet’s atmosphere and specular reflection (glint) from its ocean to study Earth-like extrasolar planets. In principle we can map the extrasolar planet’s continental boundaries by observing the glint from its oceans periodically varying as the rotation of the planet alternately places continents or water at the location on the sphere at which light from the star can be reflected specularly to Earth.

The concepts in this section have been described by McCullough (2007) and indepen-
Figure 2. Models images of the scenes from Figure 1 are shown for linear polarized components of light ($\perp$ or s-component above; $\parallel$ or p-component below), from McCullough (2007).

dently by others. Seager et al. (2000), Saar & Seager (2003), Hough & Lucas (2003), Stam, Hovenier, & Waters (2004), and Stam & Hovenier (2005) have examined the Rayleigh-scattered light of a hot Jupiter. Williams & Gaidos (2004) and Gaidos et al. (2006) examined the unpolarized variability of the sea-surface glint from an Earth-like extrasolar planet. Stam & Hovenier (2006) independently examined the observability of the polarized signatures of an Earth-like extrasolar planet, including Rayleigh scattering and sea-surface glint. Kuchner (2003) and Léger et al. (2004) have proposed that “ocean planets” may form from ice planets that migrate inward and melt; the surfaces of these planets would be liquid water exclusively, i.e. no continents, and it remains to be seen whether such planets would be entirely obscured by a thick steam atmosphere, or instead might have clear atmospheres like Earth’s.

Specularly reflected light, or glint, from an ocean surface may provide a useful observational tool for studying extrasolar terrestrial planets. An interesting parallel exists
Figure 3. Diurnal light curves for the Earth viewed at quadrature, from McCullough (2007). The reflectance (+ symbols) includes contributions from land, sea, atmosphere and authentic clouds; it is normalized to 1.0 for a full-phase Lambertian sphere. Twice the difference between the s- and p-components of linear polarization (dashed line) is anti-correlated with the total reflectance, because clouds increase the total reflectance while attenuating the two mechanisms for polarization, glint from the ocean and Rayleigh scattering of the clear atmosphere. Major surface features at the location where the sea-surface glint is or would be, in the case of continents, are labeled above the dashed line: the local maxima correspond to clear skies over oceans (Pacific, Indian, and Atlantic, as labeled); the local minima, to continents (Africa and South America, as labeled) or cloudy regions (between the Pacific and Indian oceans).

between using glints to image the oceans of extrasolar planets and a similar technique to image within the Earth’s turbid ocean (e.g. Moore et al. 2000). In the latter, one aims an underwater camera toward the sea floor while illuminating the camera’s field of view with a laser beam. Laser light scattered by the ocean water creates a haze of light visible by the camera, but the laser light that reaches the sea floor creates a well-defined spot that is also detected by the camera. By scanning the laser across the sea floor and simultaneously recording the location and brightness of the peak of the image, the light scattered by the turbid water is suppressed and detection of objects on the sea floor is enhanced. In the proposed technique for imaging extrasolar planets, the glint acts like the localized spot of the laser beam, and the rotation of the planet under the glint serves much the same purpose as the scanning of the laser beam. The polarization of the glint allows one to isolate it from the less-polarized reflection from other regions on the surface, and from the nearly-unpolarized star light scattered in the telescope optics. In the underwater technique, the monochromatic color of the laser’s light can be used to increase its contrast over any ambient light.

† Also, the laser can be pulsed.
ization, the glint and atmospheric Rayleigh scattering, can be differentiated with color, since the former is nearly achromatic whereas the latter depends strongly on wavelength.

Detection of sea-surface glints would differentiate ocean-bearing terrestrial planets, i.e. those similar to Earth, from other terrestrial extrasolar planets. The brightness and degree of polarization of both sea-surface glints and atmospheric Rayleigh scattering are strong functions of the phase angle of the extrasolar planet (see McCullough 2007). The difference of the two orthogonal linearly polarized reflectances may be an important observational signature of Rayleigh scattering or glint. The difference attributable to Rayleigh scattering peaks near quadrature, i.e. near maximum elongation of a circular orbit. The difference attributable to glint peaks in crescent phase, and in crescent phase the total (unpolarized) reflectance of the glint also is maximized. The reader intrigued by this short summary will find additional detail in McCullough (2007) and references therein.

3. Context and Digressions

As quoted in his son’s book (Dyson 2002), Freeman Dyson wrote in May 1958,

We shall know what we go to Mars for, only after we get there.... You might as well ask Columbus why he wasted his time discovering America when he could have been improving the methods of Spanish sheep-farming. It is lucky that the U.S. Government like Queen Isabella is willing to pay for the ships.

In the case of the Earth’s Moon, we have been there already, and to me, the potential tangible benefits of lunar exploration are not as clear as the intangible benefit of inspiring people to reach collectively for grand accomplishments. Preparing for this conference has caused me to consider many things that I wouldn’t have otherwise. In this section I digress to consider (in order) the relative cost of NASA, some potential risks of the US not exploring the Moon, a significant budgetary challenge to sustaining that initiative, some benefits and concomitant risks of the lunar-exploration initiative.

Humans commonly redefine large quantities in appropriate units, such as the A.U. for solar system distances, or the parsec for stellar distances. I need to do the same for the large sums of money associated with lunar exploration. Financially, NASA is approximately equivalent to a single large corporation. The median market capitalization of the 30 corporations in the Dow Jones Industrial Average is 108 B USD (as of Oct 31, 2006). One such corporation, Pfizer, a pharmaceutical company founded in 1849 and headquartered in NYC, in 2005 had annual revenue of 51 B USD and spent 7 B USD on R&D. NASA by comparison was awarded 16 B USD in 2005 by the US Congress.

The net worth of US households in 2000 was 50 T USD. The aggregate value of corporate equities directly held was 9 T USD in 2000 and was 4 T USD in 2003, so it declined approximately 2 T USD per year for three consecutive years. That is 2000 B USD per year, or 1 B USD per hour of each and every working day for three years. Although it is hard for me as an individual to grasp these large sums, these comparisons may help put into context that NASA’s lunar exploration initiative is expensive in one sense but not relative to the richness and power of our society, and especially not in comparison to those of the global society.

Returning to the Moon may make sense when one considers the potential risks or costs to the USA of not returning to the Moon when other nations do. Each nation may have

† In this and the other examples, I quote financial figures for the US because they were readily available to me on the Web (Yardeni 2004) and because this conference is primarily addressing the US-NASA initiative to return to the Moon.
a self-interest in establishing a presence on the Moon, much like Antarctica, in order to assure that no single nation monopolizes it. As someone once said when asked how much the US should spend on science,

We should spend exactly as much in each field as makes us first in that field.

If a competitor were to establish a presence on the Moon, the US might worry that it was missing out on something of which it was not aware. Here, I am reminded of Seward’s Folly, the purchase of Alaska, which in fact was both a strategic windfall and an economic bargain.

Over the many years required to return to the Moon, there are large risks that could jeopardize the political will to continue the initiative. The largest risk, in my estimation, is the US federal budget. The aging of the “baby boom” demographic of the USA and western Europe will soon greatly increase the rate of retirements. How soon? Beginning approximately in 2010, which is 1945 (the end of World War II) plus 65 years (the nominal age of retirement), wage earners that had been paying income taxes and capitalizing equity markets will retire and begin to withdraw funds. Political recognition of this impending financial bust is evident; for example, on Jan 18, 2007, US Federal Reserve Chairman Ben Bernanke testified on this specific topic before the Senate Budget Committee, “We are experiencing what seems likely to be the calm before the storm....”

If somehow that bust does not materialize, or the lunar exploration initiative somehow is immune to its effects, I expect a very substantial, albeit largely intangible, benefit of lunar exploration may be to bring the peoples of the world closer together, to save ourselves from ourselves. An excellent treatise on the latter topic was written at the time of the Apollo program, “The Tragedy of the Commons” by Garrett Hardin (1968). Hardin argues well that some problems do not have a technical solution. He also points out that scientists, and often policy makers as well, often assume that a technical solution exists and fruitlessly seek one in their faith that one will eventually be found. (Consider global climate change.) Perhaps colonization of the Moon will be a metaphor for solving Earth’s geopolitical problems. For example, a quasi-sustainable presence on the Moon wouldn’t use fossil fuels; it would use solar or nuclear power with a considerable emphasis on conservation.

Due to the large expense, in energy or dollars, of moving mass from the surface of Earth to the surface of the Moon, nuclear power, in any of the various forms of radioisotope thermoelectric generators, reactors, or explosives, may be convenient for lunar exploration for electrical power, transmuting elements in situ, or excavations. However, any such convenience, i.e. of anything brought from Earth, should be considered a negative compared to the long-term strategic benefit of “living off the land (regolith).” For example, solar power is readily and abundantly available on the lunar surface, and a large, slow flywheel utilizing compacted regolith for mass could provide for the variable power demands of human habitation and/or store power through the lunar night away from the poles. An alternative approach would be to bring from Earth a high-speed, precision flywheel of relatively small mass or a chemical battery, but those are antithetical to the strategic benefit of utilizing lunar resources. From the opposite perspective, utilizing any water ice mined from lunar craters, for human consumption and/or rocket fuel, could be myopic exploitation and destruction of an important scientific resource.

The benefits of knowledge always have had concomitant negative consequences:

The idea that curiosity leads to disaster has an ancient pedigree. Pandora opened the gods’ box and let loose all the evils of the world; the descendants of Noah built

‡ Regretably, I cannot recall the exact quotation or who said it.
the Tower of Babel to reach heaven, but God scattered them and confounded their language; Icarus flew so close to the sun that his homemade wings melted, and he fell into the sea and drowned; Eve ate the apple of knowledge and was exiled from the Garden of Eden; Faust traded his soul for sorcery and spent eternity in hell.... We believe that curiosity is the beginning of knowledge and especially of science, but we know that the application of science has led to disaster. – Finkbeiner (2006).

Neils Bohr, as attributed by Rhodes (1986), believed the knowledge of nuclear weapons would “foreclose the nation-state,” by which he meant that knowledge of nuclear weapons was so powerful that its proliferation would make the nation-state obsolete. Today, one might imagine any number of Pandora’s boxes equally well in that role, but none yet that have been opened (at least not for long) outside governmental control. It seems to me an inevitability akin to the second law of thermodynamics that diffusion of knowledge will occur, whether or not that diffusion is good for humankind. Technology increasingly amplifies the power of an individual, or a small group of individuals, for good or for evil.

As Archimedes said of the lever,

Give me a place to stand on, and I will move the Earth.

Here I suggest the lesser task of moving an asteroid, as an example of something that seems entirely fanciful now, but which may not be so in decades hence. Consider again the example given in the introduction, of Captain Cook’s voyage: at that time, it required government sponsorship, whereas today’s transportation and technical infrastructure make replicating the feat entirely within the capacity of a private individual.

Astronomers have suggested that they may give early warning of an asteroid on a collision course with Earth. Technologies useful to measuring the orbit of such an asteroid with precision sufficient to enable the prediction of an impending collision, and especially those technologies useful to perturbing it to prevent a collision, are vaguely understood and only potentially available to powerful nations today. Mostly, those nations lack a specific motivation to act. However, in some number of decades, what would have required the concerted effort of a nation or nations might be accomplished by a group of individuals, but instead of preventing a collision, that group could attempt clandestinely to create a collision from what naturally would have been a near miss. Even a credible threat to do so would be influential. Presumably it is more difficult to turn a near miss into a collision than vice versa, and today we may take solace in our confidence that such a concept is entirely impractical. My purpose is to illustrate the duality of technology’s amplification of power to individuals with a novel example potentially relevant to the lunar exploration initiative and related technologies. For those that reasonably consider the proposition patently absurd, I recite with intentional irony Margaret Mead,

Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it is the only thing that ever has.

4. Conclusions

An indirect method of imaging the oceans and continental boundaries of extrasolar planets is outlined. Results from simulations of Earth-like extrasolar planets (McCullough 2007) are presented in Section 2 and demonstrate that the difference of fluxes in two orthogonal linear polarizations is modulated by the planet’s rotation, as it alternately places continents or water at the location on the sphere at which light from the star can be reflected specularly to Earth. Section 5 digresses into the lunar exploration initiative’s potential impacts on society and vice versa.
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