The Sun Radiates Isotropically
Detailed Response to the caught zomb from *poly* on
"Direction of Radiation from the Sun"
As described at www.zombal.com
Report by *dragozzine*
Darin Ragozzine, Ph.D.

Zomb Statement:
It's usually said that the Sun emits radiation equally (and implied, with identical spectrum) in all directions. Is there any practical (non-theoretical) proof or disproof of this?

What I'm looking for is whether the Sun's emissions from its poles are any different (and if they differ in spectra) from its equatorial radiation. Please bid on this basis. (ZBL#150).

Response
Abstract: There are many theoretical, observational, empirical, and other arguments that show that the Sun's polar radiation is essentially identical as from it's equator. This can be shown by applying the astronomical theoretical understanding of blackbody radiation, limb darkening, gravity darkening, and stellar photospheres, in conjunction with direct solar observations from many directions via NASA space missions and detailed observations of stars.

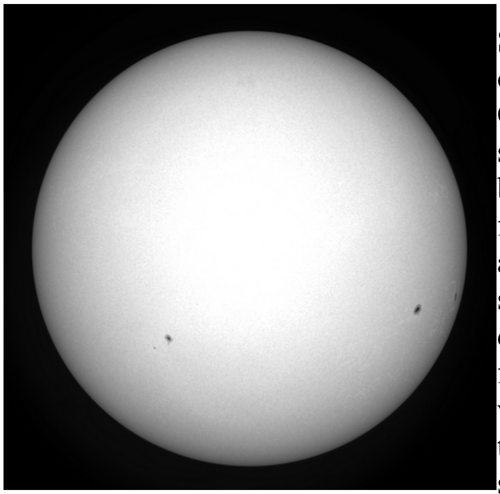
The photosphere is the region of the Sun that emits light that freely emanates throughout space to the Earth and our observatories. The properties of the hot (5700 Kelvin) plasma at the photosphere are the primary determination of the photometric and spectroscopic properties of sunlight[1]. The question about whether the Sun radiates equally in all directions is, thus, really twofold: 1) are the properties of the photosphere different at the equator and the poles and 2) is light emitted from the photosphere equally in all directions. We'll use the astronomical term for "equally in all directions", which is isotropic (as opposed to anisotropic, which can either have a preferential direction or just random noise that is technically not perfectly spherical symmetric).

We will not consider the effects of sunspots (visibly dark patches of light where cooler regions dominate the flux due to magnetic fields) or small scale variability on the Sun, known as "granulation" and caused by convection (the vigorous motion of hot and cold parcels of plasma, trying to transport heat out of the stellar interior like boiling water). Concerning isotropic emission, it is worth noting that sunspots are usually confined to two very small latitude bands and that these bands slowly shift in time[2]. The same is seen on other stars[3].

Returning now to the two questions posed earlier, we will begin with the second question: is light emitted from the photosphere isotropically? This is really a physics question about how hot bodies emit light. The light emitted from hot bodies is called "blackbody radiation" and is known to be completely isotropic; that is, there is no preferential direction. This has been studied in laboratories countless times (implicitly or explicitly) with no evidence for anisotropy. Blackbody radation combined with the laws

1 Throughout this document, I'll use "photometric" to mean light as observed over broad wavelength regimes (e.g., optical so-called "white light" photometry) and "spectroscopic" to mean the distribution of the intensity of light as a function of wavelength with a much higher resolution (e.g., 0.1 nm).
2 For more information on this, you can look up "active latitudes", "solar cycles" and "butterfly diagram" on wikipedia.
3 Sanchis-Ojeda & Winn 2011 have a great example of this seen for HAT-P-11, which has a planet that crosses over these active bands, as observed by the NASA Kepler Space Telescope.

of "radiative transfer" (effectively, how light and matter interact) can be used to create very complicated models of stellar atmospheres. These models have been shown to be correct in virtually all particulars, with mountains of data validating the laws of radiative transfer.



Shown on the left is a picture of the Sun at 450 nm (blue light) on October 6, 2012 taken by NASA's Solar Dynamics Observatory (SDO).[4] After disregarding the sunspots and other small scale variability, there is a clear trend that the Sun is brighter in the middle and darker around the edges. Although at first glance this seems to contradict the isotropic hypothesis, it is actually very well explained and understood in the context of stellar radiative transfer models. This effect is known as "limb darkening" and is due to the fact that any observer can see further down into a star's photosphere at the very center, since we're looking at this part straight on. Near the edges, any light that gets to us has to travel through more stellar atmosphere and so we don't see as deep. Stars get hotter as you go deeper and blackbody radiation is well-known to be brighter for hotter objects. So, *every* observer sees a limb darkened star and the predictions of stellar models are in extremely good agreement of the measurement of limb darkening in both the Sun and around other stars.

One way to think about this is to realize that the Sun is virtually completely spherically symmetric, including its atmosphere. What part of the atmosphere (the "photosphere") we see depends on our observing direction. An analogy for this observing fish in an aquarium. Since our eyes and brains are used to watching things in a medium (air) that does not significantly interact with light, when a different medium is used (water or stellar plasma), many simple physical phenomena become confusing. When watching an aquarium, it can appear to change size and content based on which direction you observe from, though, of course, it's actual size and content are fixed. The same can be said for watching stars and limb darkening is the classic example. In both cases, the laws of physics have been proven correct observationally.

NASA knows that the Sun appears identically limb darkened for different observers for certain because it has many different observatories that are watching the Sun from many different angles. In particular, the STEREO mission launched two satellites into orbits somewhat similar to the Earth's in such a way that they are looking at two (mostly) different parts of the Sun at the same time. These missions confirm that the Sun emits isotropically.

However, these missions are still looking at two different places on the Sun's equator. So perhaps something interesting at the pole could escape notice? Not really. First, note that the image shows that I can measure light all the way up to the edge of the Sun. Second, the Sun's axis is tilted relative to the Earth's orbit by about 7 degrees. So, these images often include the actual North or South pole of the Sun (depending). A more direct polar view might be nice, but would not reveal any significant amount of new information.

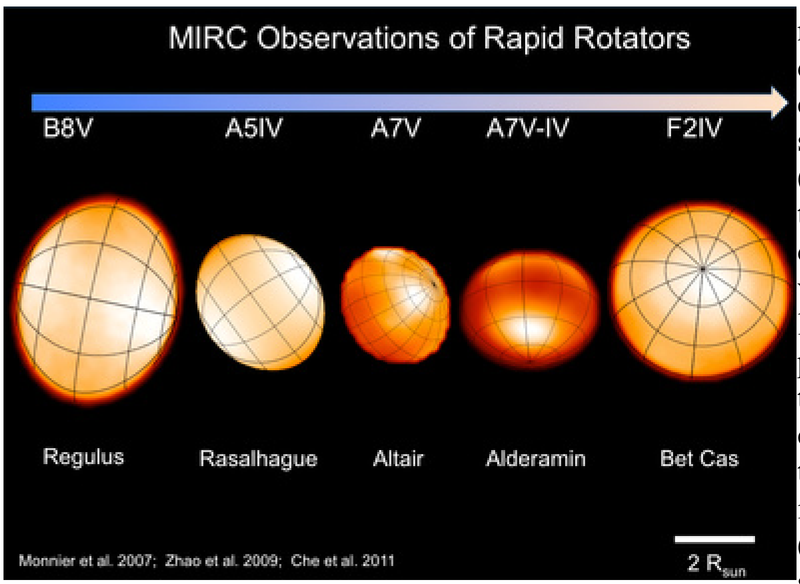
One NASA mission wanted to understand how the Sun's magnetic field structure and other properties as seen from the Sun's poles. The Ulysses mission was launched into a highly inclined polar orbit. It measured many new things about the Sun's magnetic fields, but nothing that significantly altered our

4 Constantly up-to-date pictures of the Sun in many wavelengths are available at http://umbra.nascom.nasa.gov/images/ and other websites.

models of how the Sun works. Ulysses did not have an imager, apparently, so we have no pictures of the Sun from directly looking at its pole (which would be fun to see, even if we know what to expect).

However, astronomers have a million times over shown that the Sun is merely the closest star. Dozens of stars that are very similar to the Sun (so-called “solar twins”) have been identified, many of which match the physical, photometric, and spectroscopic properties of the Sun at a very high level (e.g., differences of <10 degrees Kelvin, very impressive when stars range from 3000-20000 degrees). We see these stars from a wide variety of angles; some equator-on, others pole-on. Sometimes we even know about the orientation of their spin axes relative to our line of sight. Under the very reasonable assumption that these stars are effectively identical to the Sun, we see no unusual change in the behavior of stars that are observed pole on, compared to those that are observed equator-on. This is direct observational evidence that stars emit isotropically.

However, there is one strong exception to the above observations. It has to do with the first point raised several paragraphs ago: is the photosphere near the equator and near the edges the same? Besides limb darkening, there is one other main effect in determining what part of the photosphere is seen, called “gravity darkening”. This is a more complicated effect, but is only seen in rapidly rotating stars (and virtually all rapidly rotating stars are much hotter than the Sun). With gravity darkening, the centrifugal force is causing the local strength of gravity to be significantly different at the equator (where the apparent gravity is weaker) than at the pole. A result from three-dimesional radiative transfer called the von Zeipel Theorem predicts that the local emergent flux should be proportional to the local apparent gravity, though this effect is much much more complicated and assumption-based that the limb darkening case. However, using interferometry to actually resolve stars (i.e., seeing them as more than just a single point of light), we have clearly observationally detected the effect of gravity darkening (as seen in the Figure). It is also detected in numerous eclipsing binaries where the change in brightness of the system as the stars pass over one another clearly indicates the presence of gravity darkening, although not always in line with the rough theoretical predictions.



The Sun's rotational period is 25 days, which suggests a change in the local gravity of approximately a factor of 0.00002. So, the Sun may be very slightly brighter at the poles. This is so small, that I suspect no one has measured it.

All of the above discussion is relevant to photometric and spectroscopic measurements. One additional difference that might affect spectroscopic measurements is if the abundance of specific elements that produce spectral lines is different at the pole vs. the equator. It is the case that the photosphere has some dependence and that, in fact, in some spectral lines, you have “limb brightening” instead of limb darkening, since seeing further in the photosphere just allows for a particular element to absorb more light. However, there is no expectation that the distribution of elements on the Sun would cause any significant difference between the pole and the equator. Observationally, many spectra are taken on many points of the Sun each day which (after correcting for limb darkening and other small well -understood effects) also confirm that the Sun is homogeneously and isotropically emitting even at the spectroscopic level.

While there may be minute differences due to known or expected effects, the Sun emits radiation evenly in all directions according to a massive amount of theory, many many many observational considerations, and the combination of the two.

Please let me know if any of the above arguments are unclear or if you have any other questions or zombs. Doing a Google or Wikipedia search on most of the above concepts will provide helpful insights and references. Other bibliographic citations are available upon request, although most of this material would be covered in graduate-level textbooks on stellar interiors and atmospheres.

Thank you for this opportunity.

Dr. Ragozzine is a Postdoctoral Researcher in the Astronomy Department at the University of Florida. He is currently funded by the United States National Aeronautics and Space Administration (NASA) to work on the NASA Kepler Space Mission. This document is his personal composition and reflects his personal opinion, not that of the University of Florida, NASA, or any other party. He has many years of research experience in the orbital dynamics of planetary systems, the Kuiper belt within our own solar system, and extra-solar planets observed around other stars. His understanding of stellar atmospheres comes from graduate level astronomy courses as well as significant study of stellar properties (e.g., limb darkening) that are essential for understanding the transits of planets around other stars.