# AVIATION RADIATION

## REVIEWING THE IMPACT OF EXTRATERRESTRIAL RADIATION ON BIOLOGICAL DOSE AT HIGH ALTITUDE

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# Abstract

The risk associated with in-flight radiation exposure is incredibly obscure to the average person. Most trust that the government has regulations in place to ensure safety to both passengers of commercial airliners and their crew, but such trust is best given from an informed position. This paper serves to review the sources of extraterrestrial radiation as well as the natural shields that are in place to protect Earth from incident extraterrestrial radiation. It is found that biological dose varies significantly with respect to many variables. These variables include both terrestrial and solar weather patterns as well as flight paths and altitudes. Despite this variation, the probability of a frequent flier experiencing a dose in excess of the International Commission on Radiological Protection (ICRP) regulations is small. Even Presidential candidates on campaign, whom are amongst the population which spend the most amount of time in-flight, are not subject to appreciable increases in risk associated with biological dose.

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# Introduction

The potential for increased radiation exposure exists throughout the daily activities of many Americans, yet this potential is never really contemplated by the general public. Whether the activity is getting an x-ray at the doctor or dentist's office, sitting in front of that old cathode-ray television set at your grandmother's house, or flying back home from your grandmother's house to the comfort of your newfangled LED SmartTV, there is a quantifiable associated increase in radiation dose. While the vast majority of these increases in radiation dose are below the limits set by the International Commission on Radiological Protection (ICRP), it is beneficial to have a proper understanding of how close to the limit one gets during a particular activity. This is especially prudent for activities where the increase in radiation dose is dependent on outside and uncontrollable factors. It is reasonable to conclude that x-ray machines are carefully calibrated and operated to ensure minimal variation in radiation dose between sessions. Similarly, the fluence from a cathode-ray television set is largely constant. All variation in dose is due to viewer action, such as watching for longer periods of time or sitting closer to the screen. Flying, on the other hand, is a perfect example of an activity where the associated radiation dose is dependent on many outside factors. This paper will explore the key variables responsible for one's radiation dose during flight, as well as provide a risk assessment as it pertains to the 2016 Presidential Candidates flying around the country so much for their respective campaigns. This will be accomplished by first discussing the sources of radiation incident upon Earth from space, followed by the natural shields against said sources. Finally, the theoretically and experimentally determined doses are compared and a biological risk assessment performed.

# Part 1 – The Source

When flying across the country, the radiation of interest originates from outer space. There are two sources of extra-terrestrial radiation that must be accounted for. The first, and most obvious, is solar radiation.

Solar radiation is defined as the collective sum of all the electromagnetic radiation emitted by the Sun. The average flux upon reaching earth is 1.3615 kW/m$^2$, or 81.65 kJ/m$^2$/second. This average flux is more commonly known as the solar constant (SC) [1]. Were the solar constant 100% absorbed during the flight, the average human (mass=80.7 kg, surface area = 1.9 m$^2$) would be subject to an absorbed dose of approximately 1.92 kGy/second! Luckily, the vast majority of solar radiation is emitted in the visible spectrum or lower, with only a small fraction emitted in the biologically hazardous range. The biologically hazardous range of the solar spectrum consist of those photons which are skin-penetrating, namely the ultraviolet and x-ray regions. According to the University of California – Berkeley, approximately 10% of solar radiation is emitted in the biologically hazardous range [2]. For the purposes of determining radiation dose and associated risks during flight, it is appropriate to define a 'hazardous solar constant' (HSC). The HSC will be defined as the portion of the solar constant that exists in the x-ray and ultraviolet region. This equates to 10% of 1.3615 kW/m$^2$, or 136.15 W/m$^2$. Were 100% of the HSC absorbed uniformly by the average human during flight, the absorbed dose would be 3.2 Gy/s. In addition to the electromagnetic radiation emitted by the sun, there is also radiation emitted in the form of solar wind. Solar wind is defined as the stream of charged particles released from the upper atmosphere of the sun, consisting primarily of electrons, protons, and alpha particles. The energy associated with solar wind is approximately 1.5 to 10 keV. [3] The values stated thus far are time-averaged values. The reality is that solar emissions vary significantly with respect to processes intrinsic to the Sun. The most prominent of these processes is the solar magnetic activity cycle. Operating with an average period of roughly 11 years, the solar magnetic activity cycle (solar cycle for short) describes the sinusoidal variation in the number of sunspots on the surface of the sun. The term solar maximum describes the period of time where the number of sunspots is largest, while solar minimum refers to the opposite. [4]

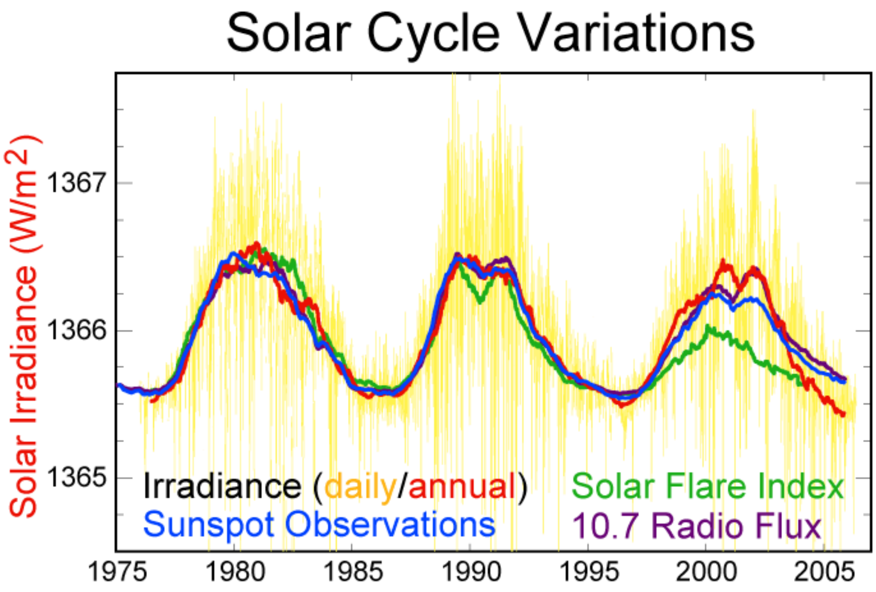

Figure 1 – Sinusoidal oscillation in solar emission as a function of time. The portion of ambient radiation dose that can be attributed to solar emissions is reasonably concluded to increase during times of solar maximum and decrease during times of solar minimum. Extrapolating from the above figure, one may reasonably conclude that the Sun is currently experiencing a solar minimum. [F1]

Another major event intrinsic to the Sun responsible for large increases in emission is the coronal mass ejection (CME). The CME is a process by which unusually large amounts of plasma are released from the Sun into the solar wind. Approximately three CMEs occur daily during solar maximum, while there is an average of one CME during solar minimum. [5]

The second source of extra-terrestrial radiation incident upon earth is from cosmic events such as supernovae. Cosmic radiation is super high-energy (up to $10^{20}$ eV) radiation originating from outside of the solar system. Primary cosmic radiation consists of 99% protons and alpha particles, approximately 1% of heavier charged nuclei, and an extremely minute amount of positrons and antiprotons. Secondary cosmic radiation is caused by the decay of primary cosmic radiation as they impact an atmosphere, and consists primarily of neutrons, pions, muons, and positrons. The cosmic flux at the upper portion of Earth's atmosphere is largely dependent on the Earth's magnetic field, the energy of the comic radiation, and on the solar wind. [6]

# Part 2 – The Shielding

Now that the nature of the radiation sources as they pertain to in-flight dose have been explored, it is necessary to determine how much of this radiation actually makes it to the altitude that airplanes operate at. The natural shielding between the source of cosmic radiation and earth will first be discussed, followed by the shielding between the Sun and Earth.

The most effective of natural shield against cosmic radiation are the solar winds. Solar wind undergoes a transition - the termination shock - at approximately 94 astronomical-units (AU).

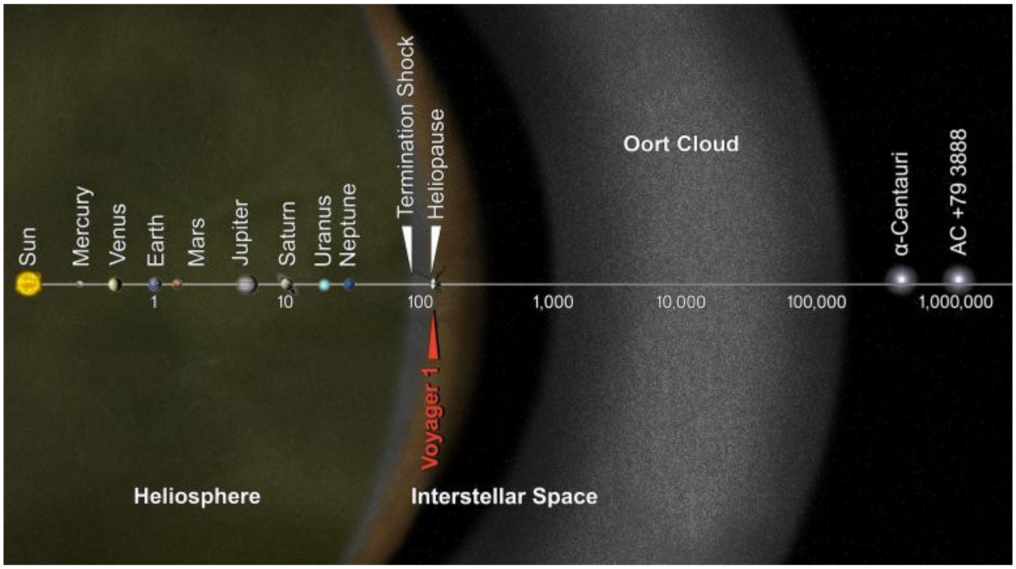

Figure 2 - The solar system and closest neighbors. The axis is a measure of astronomical units (AU) from the Sun. It can be seen that the termination shock is in all practicality a shield against cosmic radiation protecting the entire heliosphere. [F2]

This termination shock results in the speed of the solar wind decreasing from supersonic to subsonic. This decrease in velocity causes an increase in density which in turn raises the probability of interaction between the outward flowing solar wind and inward-flowing cosmic radiation. This region between the termination shock and the edge of the solar atmosphere – the heliopause - serves as a shield to cosmic radiation, decreasing the flux at energies below 1 GeV by approximately 90%. [7]

The magnetic field of the Earth also contributes significantly to the natural shielding against cosmic radiation. The nature of this shielding is one of deflection. As cosmic radiation approaches Earth, the magnetosheath affects the radiation velocity in such a way that it does not intercept the Earth. This process also serves to shield the Earth from incident solar wind.

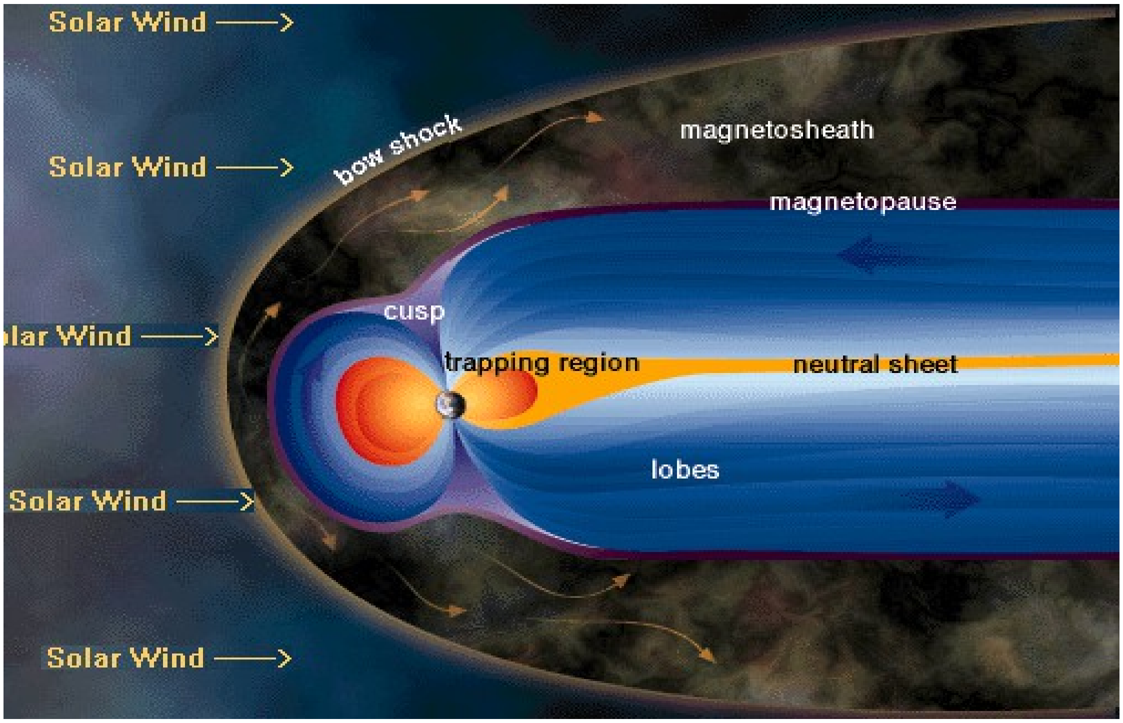

Figure 3 – The deflection of solar wind/cosmic radiation as it approaches the magnetosphere. It can be seen that interplanetary travel through the neutral sheet would best protect against dose due to solar wind and cosmic radiation. [F3]

However, solar events can cause the integrity of the magnetosphere to falter. In the event that a CME is directed towards the Earth and reaches it, the shock wave of solar particles caused by the interplanetary CME (ICME) causes a geomagnetic storm that may disrupt the Earth's magnetosphere. During these events, humans at high altitudes such as airplanes and space stations are at risk to far greater dose from cosmic radiation due to the weakening of the magnetosphere. [8] The probability of an ICME is rather low on an annual basis, however NASA estimates that there is a 12% chance that an ICME occurs between 2012 and 2022. [9]

Variations in magnetic field as a function of latitude, longitude, and azimuthal angel suggest similar variations in cosmic radiation flux incident upon Earth as a function of latitude, longitude, and azimuthal angel. Experiment has determined approximately 200 cosmic particles with energy on the order of MeV strike every square meter on Earth every second. Higher energy comic particles are far rarer. Cosmic particles on the order of $10^{18}$ eV and greater strike upon a square-kilometer only once a week, while cosmic particles on the order of $10^{20}$ eV and greater strike the same area once a century. [10]

Natural shielding against the HSC is done exclusively within the Earth's atmosphere. Modeling this process exactly is extremely complicated. The true spectrum of the HSC varies with properties and events intrinsic to the Sun, and atmospheric attenuation is dependent on terrestrial properties and events such as the weather and the eruption of Thera. [11] Additionally, the atmosphere itself does not have uniform properties. The physical characteristics of the troposphere (the lowest portion where weather effects occur) are quite different than the mesosphere (the middle portion) and the exosphere (the portion closest to outer space as least particle-dense). However, there is one portion of the atmosphere that is the most significant in affecting radiation dose of extraterrestrial origin. Ionized by the incoming solar and cosmic radiation, the ionosphere serves to attenuate the vast majority of incoming extraterrestrial radiation. [12]

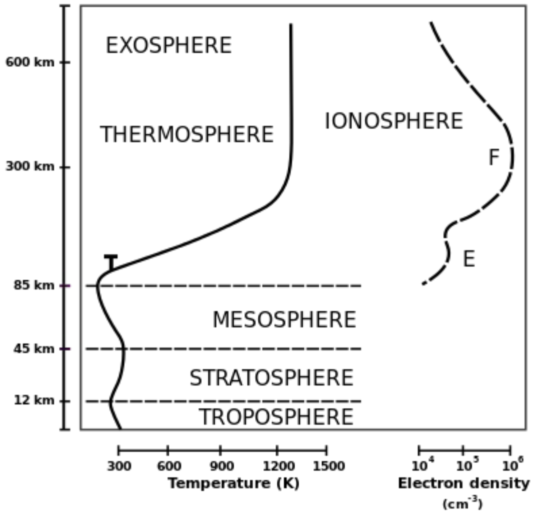

Figure 4 – The ionosphere represents the altitude where the majority of incoming extraterrestrial radiation is attenuated. It can be seen that radiation shielding is of vital importance when traversing the ionosphere. [F4]

The altitude of standard commercial flights is far below the ionosphere (commercial airliners barely get above the troposphere). Therefore, fluctuations in ambient dose received while in flight will require significant fluctuations in source properties and/or natural shielding beyond the ionosphere. The ICME is a perfect example of the aforementioned significant ‘fluctuation’.

The final and perhaps most popular natural shield against solar radiation is the ozone layer. The ozone layer is heavily populated by the oxygen isotope $O_3$, for which the zone is named after. The attenuation cross section for UV radiation incident upon ozone is incredibly high. In fact, the effectiveness is so high that the integral DNA action spectrum is significantly reduced. The DNA action spectrum is a measure for the relative effectiveness, as a function of energy, UV radiation has to cause damage to DNA. [13]

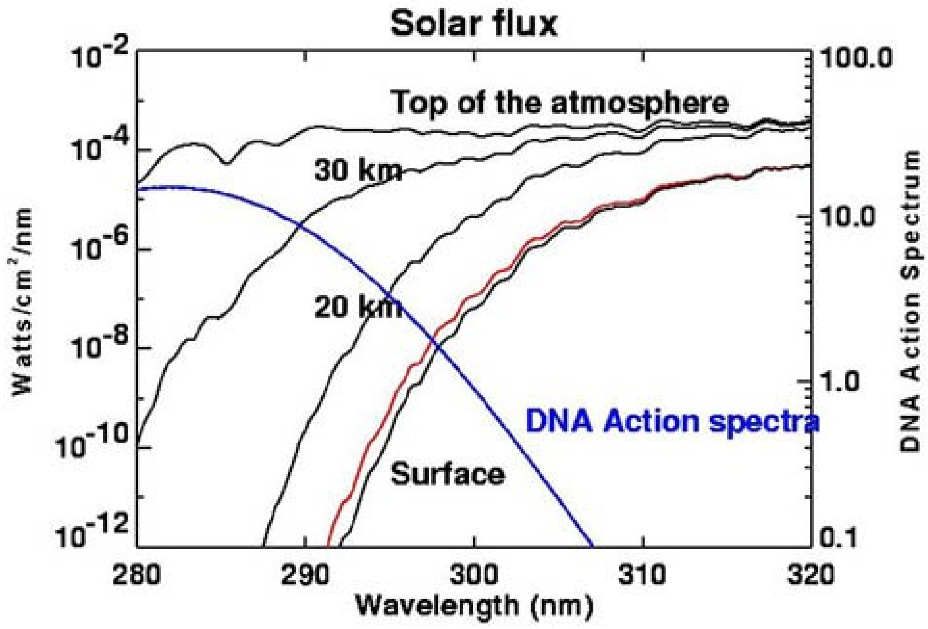

Figure 5 – Juxtaposition of the DNA action spectra as a function of wavelength with the solar flux as a function of wavelength for various altitudes. The red line represents surface flux with a 10% reduction in ozone concentration. [F5]

The ozone layer is not without weakness, however. There are many industrial chemicals that lead to the depletion of the ozone concentration and therefore a less effective shield against the HSC. Chlorofluorocarbons (CFCs), the most popular chemical used for refrigeration, is also the most popular of ozone depleting chemicals. The effects of such chemicals are so risky and unpopular that the first unanimously passed measure by the United Nations occurred with the Vienna Convention for the Protection of the Ozone layer in 1985. This accord, alongside the succeeding Montreal Protocol (1989), calls for a worldwide curtail in production of ozone depleting chemicals. [14] [15]

Not all the shielding between the frequent flier and harmful space-radiation is natural. Significant research and effort is put into determining the best methods for keeping passenger and crew radiation doses as low as reasonably achievable. The primary contributor to these efforts is NASA, as the necessary investment in radiation shielding for human spaceflight is far greater than commercial air travel. [16] Under the burden of maximizing profits, commercial airliners are forced to weigh the relative safety benefit of outfitting their planes with optimal radiation shielding against the economic benefit of using less-effective shields and thereby reducing the total weight of the vehicle. [17] The exact weighting that a given airliner/airplane manufacturer assigns to radiation protection versus economic benefit and cost reduction is proprietary, however it is safe to assume that the commercial airline industry does not invest as much in safety as NASA. This is not unlike how the United States Navy invests far more into the safety and security of their reactors as compared to the commercial nuclear power industry. When economic return isn't a factor in design, system may be created much safer.

## Part 3 – The Dose

Many studies have been performed on ambient in-flight radiation levels. This is to be expected, as the Occupational Safety and Health Administration (OSHA) would have a field day with the Federal Aviation Administration (FAA) if it were shown that aviation working conditions are correlated with an increase in cancer risk. Findings include that the average annual occupational dose is 1-6 mSv and that the cumulative lifetime dose does not exceed 80 mSV. [18] [19] This occupational dose is within the ICRP guideline of 20 mSv annual occupational exposure averaged over 5 years.

However, investigation of additional articles suggests that the instantaneous inflight radiation dose varies significantly with respect to ICRP guidelines. The Society for Radiological Protection, for example, released a paper this year concluding that passengers in North America exceed ICRP annual dose limits at an average of 420 flight-hours per year, down to 120 flight hours on specified routes under maximum exposure conditions. Additionally, the study concludes that solar activity plays a significant role in determining annual dose as North America can see a 35.2% increase in dose during solar minimum and 18.4% decrease during solar maximum. [20] This is a 53.6% variation over the course of 11 years. Assuming a 40 hour work week, taking half the 52-week year for vacation, and only being in-flight for half the work week, that gives 520 flight-hours per year in occupational dose. Therefore, it is reasonable to conclude that non-trained frequent fliers of the public may experience a much greater risk than the aviation employees themselves. [21]

## Part 4 – The Risk

Research shows that the true dose associated with commercial flight appears to be quite variable. It is statistically certain that some frequent fliers experience annual doses higher than ICRP guidelines for the general public. Utilizing the conservative linear no-threshold model, there is indeed an increase in cancer risk. However, the Nuclear Regulatory Commission states that public health data does not absolutely establish the occurrence of cancer below approximately 100 mSv. [22]

The bottom line is that the risk associated with biological dose from air travel can be significant under the right circumstances. For example, if one was travelling in an airplane across the north-pole during a summer ICME, their risk would be at a maximum. This may be compared to circumstances where the risk for biological dose is at a minimum, which would be a regional flight within southern Europe or North America at night time during the winter under solar minimum. In the interest of keeping the radiation dose as low as reasonably achievable, it is necessary for the aviation industry to track meteorological processes of both the Earth and Sun. In addition to meteorological processes, orbital mechanics and flight trajectories also play a large role in determining the true dose as the view factor between the Sun and an airplane can vary dramatically. Indeed, the airline industry does reroute flights in response to solar events in order to keep the dose to passengers and crew as low as reasonably achievable. [23] However, it is impossible to know just how many corners the aviation industry is willing to cut when weighing economic return against the risk for biological dose to passengers and crew.

# Part 5 – What About the Candidates?

The risk for biological dose associated with air travel may be perhaps the greatest for presidential candidates during the general election. The amount of time that the candidates invest in jet-setting across the country for court voters is almost certainly greater than any other member of the 'public'. Investigation into Hillary Clinton's current campaign schedule for the remainder of the summer shows that Clinton will be travelling between 20 locations that are far enough apart that ground travel would be unreasonable, including trips to Tel Aviv and Beijing. The entirety of this schedule is set to occur between May 10th and July 25th, 2016. [24] Donald Trump, on the other hand, does not have a campaign itinerary publicly available. [25] However, for competitions sake, let's assume that Trump invests a comparable amount of time in air travel as Clinton. Table 1 contains the most probable airports that Clinton will be travelling between to attend her scheduled events, as well as then fight times associated with each trip as reported by Google flights.

Table 1 – Time Invested in Air Travel by Clinton Campaign

| Trip | Flight Time (hours) |
|---|---|
| Louisville to Philadelphia | 2 |
| Philadelpia to Los Angeles | 6 |
| Los Angeles to San Francisco | 1.5 |
| San Francisco to Los Angeles | 1.5 |
| Los Angeles to Nashville | 4 |
| Nashville to Tel Aviv | 15 |
| Tel Aviv to New York City | 12 |
| New York City to Boston | 1 |
| Boston to Miami | 3.5 |
| Miami to Chicago | 3.25 |
| Chicago to Dallas | 2.5 |
| Austin to Miami | 2.75 |
| Miami to Washington, D.C. | 2.5 |
| Washington, D.C. to Los Angeles | 5.75 |
| Los Angeles to Beijing | 12.5 |
| Beijing to New York city | 13.5 |

| | |
|---|---|
| New York City to Sacramento | 6.5 |
| Sacramento to Seattle | 1.75 |
| Seattle to Philadelphia | 5 |
| Total Flight Time | 102.5 |

The total flight time invested by Hillary Clinton between May 11th and July 25th is approximately 102.5 hours. This is 102.5 hours over 75 days. Extrapolating this across the entire 181 days remaining until November 8th, 2016 when the campaign will officially end, one estimates 247 flight-hours will be invested by the Clinton campaigning in air travel for the remainder of the campaign. This is less than half of the average number of flight hours needed to exceed ICRP recommended dose. There is no reason to conclude that the Presidential candidates have any increased risk associated with biological dose due to increased flight-hours as part of their campaigns, especially during times of solar minimum.

# Summary

Modeling the risk associated with extra-terrestrial radiation is an incredibly complex process. The true spectrum that a commercial airline passenger or crewmember is exposed to at standard altitude is dependent on many outside factors. These factors include latitude and longitude of the flight path, solar cycle status, and presence of sporadic events such as interplanetary coronal mass ejections. While it is not impossible for a frequent flier to exceed ICRP recommended doses, the probability is incredibly slim, especially considering operational adaptations on behalf of the airlines and Federal Aviation Administration. Even the Presidential candidates on campaign do not face any appreciable increase in biological dose, despite spending perhaps the most time in-flight amongst members of the public.

REFERENCES

[1] Johnson, Francis. "The Solar Constant." (1954): n. pag. *American Meteorological Society*. U.S. Naval Research Laboratory, 29 Mar. 2010. Web. 10 May 2016. <http://journals.ametsoc.org/doi/citedby/10.1175/1520-0469%281954%29011%3C0431%3ATSC%3E2.0.CO%3B2>.

[2] "The Electromagnetic Spectrum." *The Electromagnetic Spectrum*. N.p., n.d. Web. 10 May 2016. <http://www.ucmp.berkeley.edu/education/dynamic/session5/sess5_electromagnetic.htm>.

[3] *Kallenrode, May-Britt (2004). Space Physics: An Introduction to Plasmas and. Springer. ISBN 3-540-20617-5.*

[4] Friis-Christensen, E., & Lassen, K. (1991). Length of the Solar Cycle: An Indicator of Solar Activity Closely Associated with Climate. *Science, 254*(5032), 698-700. doi:10.1126/science.254.5032.698

[5] Wimmer-Schweingruber, R. F. (2006). Coronal Mass Ejections. *Space Science Reviews*, *123*(1-3), 471-480. doi:10.1007/s11214-006-9025-x

[6] Fermi, E. (1949). On the origin of the cosmic radiation. *Physical Review*, *75*(8), 1169.

[7] Jokipii, J. R. (1971). Propagation of cosmic rays in the solar wind. *Reviews of Geophysics*, *9*(1), 27-87.

[8] Wilson, J. W., Wood, J. S., Shinn, J. L., Cucinotta, F. A., & Nealy, J. E. (1993). A proposed performance index for galactic cosmic ray shielding materials.

[9] Near Miss: The Solar Superstorm of July 2012 - NASA Science (Near Miss: The Solar Superstorm of July 2012 - NASA Science) http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

[10] Detection. (n.d.). Retrieved May 10, 2016, from https://www.auger.org/index.php/cosmic-rays/detection

[11] LaMoreaux, P. E. (1995). Worldwide environmental impacts from the eruption of Thera. *Environmental Geology*, *26*(3), 172-181.

[12] Kelley, M. C. (2009). *The Earth's Ionosphere: Plasma Physics & Electrodynamics* (Vol. 96). Academic press.

[13] Quaite, F. E., Sutherland, B. M., & Sutherland, J. C. (1992). Action spectrum for DMA damage in alfalfa lowers predicted impact of ozone depletion. *Nature*, *358*(6387), 576-578.

[14] Slaper, H., Velders, G. J., Daniel, J. S., de Gruijl, F. R., & van der Leun, J. C. (1996). Estimates of ozone depletion and skin cancer incidence to examine the Vienna Convention achievements. *Nature*, *384*(6606), 256-258.

[15] Murdoch, J. C., & Sandler, T. (1997). The voluntary provision of a pure public good: The case of reduced CFC emissions and the Montreal Protocol. *Journal of Public Economics*, *63*(3), 331-349.

[16] Durante, M. (2014). Space radiation protection: destination Mars. *Life sciences in space research*, *1*, 2-9.

[17] Read "Securing the Future of U.S. Air Transportation: A System in Peril" at NAP.edu. (n.d.). Retrieved May 10, 2016, from http://www.nap.edu/read/10815/chapter/6

[18] Langner, I., Blettner, M., Gundestrup, M., Storm, H., Aspholm, R., Auvinen, A., ... & Rafnsson, V. (2004). Cosmic radiation and cancer mortality among airline pilots: results from a European cohort study (ESCAPE). *Radiation and environmental biophysics*, *42*(4), 247-256.

[19] El-Jaby, S., & Richardson, R. B. (2015). Monte Carlo simulations of the secondary neutron ambient and effective dose equivalent rates from surface to suborbital altitudes and low Earth orbit. *Life sciences in space research*, *6*, 1-9.

[20] Alvarez, L. E., Eastham, S. D., & Barrett, S. R. (2016). Radiation dose to the global flying population. *Journal of Radiological Protection*, *36*(1), 93.

[21] "Chapter 14. Radiation Safety Program." (1999): n. pag. *Operations and Control Center Safety*. Federal Aviation Administration. Web. 10 May 2016. <http://www.faa.gov/documentLibrary/media/order/occ_safety/order3900/media/ch14.pdf>.

[22] Radiation Exposure and Cancer. (n.d.). Retrieved May 10, 2016, from http://www.nrc.gov/about-nrc/radiation/health-effects/rad-exposure-cancer.html

[23] Airline Diverts Aircraft During Solar Storm : DNews. (2012). Retrieved May 10, 2016, from http://news.discovery.com/space/airline-diverts-aircraft-during-solar-storm-120124.htm

[24] Hillary Clinton’s Events. (2015). Retrieved May 10, 2016, from https://www.willhillarywin.com/hillary-clintons-events/

[25] SHOW YOUR SUPPORT FOR DONALD TRUMP. (n.d.). Retrieved May 10, 2016, from https://www.donaldjtrump.com/schedule

FIGURE REFERENCES

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[F2] Lack of objects between heliopause and Oort cloud? (n.d.). Retrieved May 10, 2016, from http://astronomy.stackexchange.com/questions/13474/lack-of-objects-between-heliopause-and-oort-cloud

[F3] Space Weather Models at CCMC. (n.d.). Retrieved May 10, 2016, from http://ccmc.gsfc.nasa.gov/educational/MagnetosphereWebPage.php

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