Plume Effects on Radiation Detection by Spacecraft

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Murat Celik* and Manuel Martinez-Sanchez†
Massachusetts Institute of Technology, Cambridge, MA, 02139, USA

For space based observatories, like NASA's Terrestrial Planet Finder (TPF) project, electric propulsion systems provide an attractive alternative to traditional chemical thrusters due to their higher specific impulse and more controllable thrust levels at reasonably high efficiencies. For such telescopic observation missions, the electromagnetic radiation emission due the thruster plume particles poses a contamination concern. In this study, various radiation mechanisms in the electric thruster plume plasma are discussed. In addition to understanding the various radiation emission mechanisms, it is important to quantify the amount of plume radiation collected by the optical system of the telescope, which contaminates the observed signal. Discussions about the telescope radiation collection criteria are provided in this paper. Results are presented for the formation flying TPF infrared (IR) interferometry spacecraft using two 200W Hall thrusters using a three-dimensional hybrid-PIC DSMC plume simulation model, AQUILA, which show plume radiation emission and radiation collected by the collector.

Nomenclature

h	= Planck's constant
c	= speed of light in vacuum
k	= Boltzmann's constant
e	= elementary charge
ϵ_o	= permittivity of free space
m	= electron mass
λ	= wavelength
ν	= frequency
θ	= angular resolution
φ	= field of view angle
D	= collector mirror diameter
B_l	= interferometer baseline length
T	= electron temperature
n	= atomic energy level index
n_e	= electron density
n_i	= ion density
Z	= ion charge number
R_y	= Rydberg energy
$\overline{g}$	= Bremsstrahlung Gaunt factor
G_n	= electron-recombination Gaunt factor
$J_{photon_\lambda}(\lambda)$	= number of Bremsstrahlung photons emitted at wavelength λ
$R(\lambda)$	= Planck's radiancy function

*Graduate Student, Department of Aeronautics and Astronautics, celik@mit.edu
†Professor, Department of Aeronautics and Astronautics, mmart@mit.edu

I. Introduction

Electric thrusters are being considered for future space observatory missions due to their high specific impulse, short thrust bits, and high efficiencies. A major concern with the use of electric thrusters is the possible interactions of the thruster plume particles with the spacecraft components and operations. As a result of these concerns, there has been extensive experimental and theoretical work conducted to understand the thruster plume expansion and plume interactions with spacecraft.

One thruster plume-spacecraft interaction of concern is the contamination of the observed telescopic signal by the detection of the radiation emission from electric thruster plume plasma. There is limited understanding of the intensity of electromagnetic emission from thrusters such as Hall thrusters and ion engines, most likely electric propulsion candidates for most missions.

In an earlier paper, a numerical simulation of the plume expansion around the formation flying TPF spacecraft was presented for a hypothetical thruster firing scenario.[1] In this study, numerical simulation results of radiation emission due to plume plasma for the same hypothetical configuration are presented and the expected radiation contamination is analyzed for the various radiation emission processes.

TPF and Thruster-Spacecraft Interaction Concerns

The Terrestrial Planet Finder mission is a NASA space telescope project to look for earth-like planets capable of supporting life around the nearby stars. There are two architectures being considered for TPF: a visible coronagraph, and a formation flying infrared (IR) interferometer. For the formation flying architecture, there are several spacecraft flying in formation to form a large ($\sim 100\ m$ baseline) IR space interferometer. Electric thrusters are being considered as the most likely propulsion candidates for this project. Since the formation flying spacecraft are only a few tens of meters apart, thruster-spacecraft interactions are a major concern. Since the thruster plume from an adjacent spacecraft might get in the field of view of the collector mirrors, an analysis of the radiation emission due to plume plasma and the collection of radiation due to particles in the telescope field of view is needed.

II. Telescopic Measurements

Telescopes collect photons coming from the source of observation. Detectors are located at the focal point of the telescopic system and record information such as the intensity of the collected radiation at various frequencies as function of time. In the following subsections, several important parameters of a space telescope are listed.

A. Spectral Range

Spectral range is the range of wavelengths (frequencies) that the telescope system collects. For a telescope the spectral range of interest will be decided by the wavelength of the signal being observed. For example, for the Terrestrial Planet Finder mission, the interferometry concept operates in the wavelength range of 7 to 17 μm in order to detect the atmospheric absorption of radiation of certain wavelengths pointing at the existence of life by compounds such as oxygen, water, ozone, carbon dioxide and methane in the mid-IR frequencies, whereas the coronagraph concept of the same mission operates in the visible to near-IR wavelengths of 0.5 to 1.05 μm.

B. Field of View

The field of view of a telescope indicates the angular part of the sky that can be viewed. As the field of view gets larger, the area of sky visible to the telescope system gets larger. The desired field of view of a telescope system is decided by the largest area of the sky to be observed at a given time. For TPF, the field of view of the telescope system should span the habitable zone of the star being observed. Thus, the maximum required field of view is determined by the the closest star system observed.[2] The field of view for the TPF interferometer is 1 arcsecond.[3]

C. Angular Resolution

Angular resolution is a telescope's ability to resolve close celestial objects. Angular resolution of a telescope gives the minimum achievable angular separation between the point like astronomical sources (stars, planets, etc.). The resolving power of a lens or mirror is limited by diffraction effects. Diffraction limited angular resolution of a lens or mirror of diameter D is given by the Rayleigh criterion

$$\theta \approx 1.22 \frac{\lambda}{D} \tag{1}$$

where θ is the angular resolution in radians, and λ is the wavelength of radiation being observed. According to this equation, observations at higher wavelengths requires larger optics for the same diffraction limited angular resolution. For example, a $11 \mu m$ IR collector requires optics with a diameter ~ 20 times larger than the visible green light with a wavelength of $540 nm$ for the same angular resolution.

Interferometry is an observational technique that uses the interference of observed electromagnetic waves to increase the angular resolution of the telescope system by increasing the effective aperture diameter of a number of smaller collectors spaced some larger distance among them. The improved angular resolution is on the order of $\theta_{min} \approx \lambda / B_l$ where B_l is the baseline length, the largest distance between the collectors.

For TPF, the minimum angular resolution requirement is based on resolving a planet located at the inner edge of the habitable zone of the furthest star being observed.[2] The angular resolution for the TPF interferometer will be 50-75 milli-arcseconds.[3]

III. Plume Plasma Radiation Emission

There are two main sources of radiation that might get collected by the telescope system and interfere with the observed signal. The first source of radiation is the radiation emitted by the plume plasma particles in the field of view of the telescope. The second source of radiation is scattering of external radiation (such as solar radiation) by the plume plasma particles into the collection area of the telescopes. Discussions on the radiation emission due to plume plasma will be presented here.

The radiation emission due to plume plasma can be in the form of narrow emission lines due to electronic and molecular transitions, and broad continuum spectra due to charged particle acceleration processes. The discussions of various processes and their significance for a mission such as the formation flying interferometer concept of TPF are presented here. Since, Xenon is the most common propellant for electric thrusters, discussions assume a Xenon plasma.

A. Line Radiation

Electronic transitions between the various energy levels of Xenon's atomic and ionic states result in the emission of radiation at distinct frequencies in a narrow line form. Xenon, a high atomic number noble gas, has a complicated atomic structure, resulting in energy levels determined by the various spin and angular momentum couplings between the electronic states and with the heavy nucleus. Theoretical prediction of the intensity of the radiation emission is difficult. Experimental measurements of various collisional and radiative excitation/de-excitation processes provide information on the electronic transitions. Published experimental measurement studies of Hall thruster plume radiation emission in the visible and near-IR range of the spectrum revealed important emission lines.[4–6] Several prominent line emissions in the visible and near-IR range of the spectrum are modeled in this study. Results are used to predict line emission in the IR spectrum.

B. Continuum Radiation

When an electric charge, such as an electron, is accelerated (or decelerated) it radiates electromagnetic energy. There are three main mechanisms of such radiation emission. These processes are Bremsstrahlung radiation, electron recombination radiation, and electron cyclotron radiation.

1. Bremsstrahlung Radiation

In the Bremsstrahlung radiation process an electron is subjected to an acceleration/deceleration due to the electric field of a nearby charged particle such as an ion. As a result of this process, electromagnetic radiation is emitted. This process is pictured in Fig. 1.

$$Xe^{+} + e^{*} \rightarrow Xe^{+} + e + h\nu$$

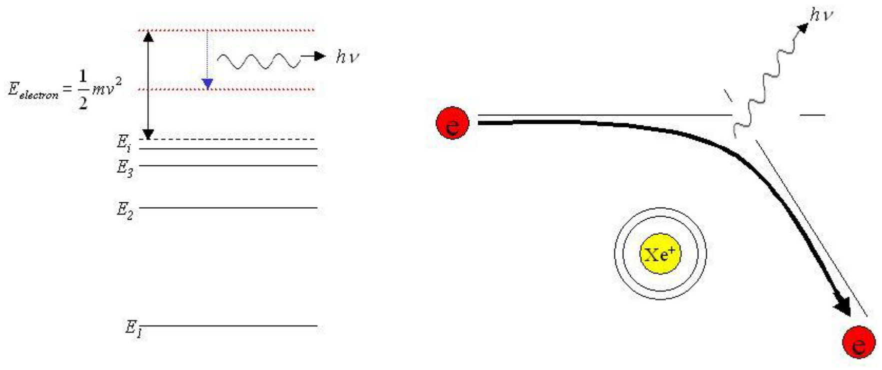

Figure 1. Bremsstrahlung radiation

For thermal (Maxwellian) electrons, the power emitted due to a Bremsstrahlung process per unit volume per unit frequency is given by the equation:

$$J(\nu) = (\frac{e^2}{4\pi\epsilon_o})^3 \frac{32\pi^2}{3\sqrt{3}m^2c^3}(\frac{2m}{\pi kT})e^{-\frac{h\nu}{kT}} n_e n_i Z^2 \overline{g} \qquad [Wm^{-3}Hz^{-1}] \tag{2}$$

Evaluating the fundamental constants in the above equation gives

$$J(\nu) = 6.321 \times 10^{-53}(\frac{T}{eV})^{-1/2} e^{-\frac{h\nu}{T}} n_e n_i Z^2 \overline{g} \qquad [Wm^{-3}Hz^{-1}] \tag{3}$$

where T has units of eV and h has units of $eV \cdot s$. The number of photons released for a given frequency range per unit volume per unit time per unit frequency can be found by the expression $J_{photon_\nu}(\nu) = J(\nu)/(h\nu)$. Similarly, the expression for the number of photons emitted at a given wavelength per unit volume per unit time per unit wavelength can be obtained by:

$$J_{photon_\lambda}(\lambda) = 9.54 \times 10^{-20}(\frac{T}{eV})^{-1/2} e^{-\frac{ch}{\lambda T}} n_e n_i Z^2 \overline{g} \qquad [m^{-3}s^{-1}m^{-1}] \tag{4}$$

For a quasi-neutral plasma of density n_e and temperature T, the number of photons released per meter cubed per second in the wavelength range of λ_1 to λ_2 will be given by:

$$\int_{\lambda_1}^{\lambda_2} J_{photon_\lambda}(\lambda) d\lambda = 9.54 \times 10^{-20}(\frac{T}{eV})^{-1/2} n_e^2 Z^2 \overline{g} \left[\Gamma(0, \frac{ch}{\lambda_2 T}) - \Gamma(0, \frac{ch}{\lambda_1 T}) \right] \tag{5}$$

where $\Gamma[a, x]$ is the incomplete gamma function where a is a constant, and x is a variable. Using the continued fraction representation for the incomplete gamma function,[7] the above expression can be written in a form that can be easily incorporated into the computational model:

$$\int_{\lambda_1}^{\lambda_2} J_{photon_\lambda}(\lambda) d\lambda = 9.54 \times 10^{-20}(\frac{T}{eV})^{-1/2} n_e^2 Z^2 \overline{g} \left[\frac{e^{-\frac{1.24}{T\lambda}}}{1 + \frac{1.24}{T\lambda} - \frac{1}{3 + \frac{1.24}{T\lambda} - \frac{4T\lambda}{1.24 + 5T\lambda}}} \Bigg|_{\lambda_1}^{\lambda_2} \right] \tag{6}$$

where T is in eV and λ is in μm. The above expression for the Bremsstrahlung photon emission is implemented into the hybrid-PIC Hall thruster plume code.[8–10] The results are discussed in the next section.

Using (3), for an optically thin plasma, expected radiative power losses can be calculated. For the discharge chamber of a $200W$ Hall thruster where $n_e \cong n_i \approx 10^{18}$ particles per cubic meter, and the $T \cong 30$ eV, the expected power loss due to Bremsstrahlung processes would be $\sim 10\ mW/m^3$. Similarly, for the near plume region of such a Hall thruster where $n_e \cong n_i \approx 10^{16}\ m^{-3}$, and $T \approx 3$ eV, the Bremsstrahlung power loss would be $\sim 3\ \mu W/m^3$.

2. *Electron-Recombination Radiation*

Electron recombination radiation is the radiation emitted by an accelerating (decelerating) electron in the field of a nearby charged particle during its capture by the charged particle. This process is diagramed in Fig. 2.

$$Xe^{+} + e^{*} \rightarrow Xe^{*} + h\nu$$

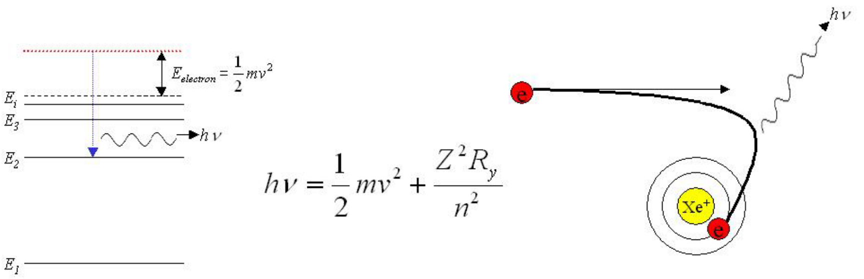

Figure 2. Electron recombination radiation

For thermal (Maxwellian) electrons, the power emitted due to an electron-recombination process per unit volume per unit frequency is given by the equation:

$$J(\nu) = (\frac{e^2}{4\pi\epsilon_o})^3 \frac{32\pi^2}{3\sqrt{3}m^2c^3} (\frac{2m}{\pi kT}) e^{-\frac{h\nu}{kT}} n_e n_i Z^2 \left[\frac{Z^2 R_y}{T} \frac{2}{n^3} e^{Z^2 R_y / n^2 T} G_n\right] \qquad [Wm^{-3}Hz^{-1}] \tag{7}$$

where G_n is the electron-recombination Gaunt factor, and R_y is the Rydberg energy and n is the principle quantum number of the recombined level. Except for the expression in the bracket, the above formula is identical to the Bremsstrahlung formula without the Gaunt factor, $\bar{g}$. Thus, the relative importance of the recombination radiation is given by the ratio:

$$\frac{Z^2 R_y}{T} \frac{2}{n^3} \frac{G_n}{\bar{g}} e^{\frac{Z^2 R_y}{n^2 T}} \tag{8}$$

Due to the n^{-3} dependence, recombination radiation is negligible for outermost (high lying) energy levels that contribute to low frequency radiation emission.[11] Thus, recombination radiation becomes small for higher wavelengths such as the IR range of the spectrum that is off concern to TPF-I.

3. *Electron Cyclotron Radiation*

Cyclotron radiation is the electromagnetic radiation emitted by charged particles moving in a magnetic field. The Lorentz force acts on the particles perpendicular to both the magnetic field lines and the velocity vector, causing the particle to spiral around the magnetic field lines, thus accelerating charged particles and causing them to emit radiation. This radiation consists of a series of discrete harmonics. For non-relativistic plasma, the emission occurs at the fundamental frequency ν_c and higher. The fundamental frequency is given by:

$$\nu_c = \frac{eB}{m} \approx 28 \cdot B \quad [GHz] \tag{9}$$

where B is the magnetic field strength in units of *Tesla*. From the equation above, it is clear that electron cyclotron emission in the infrared or visible frequency range requires extremely high magnetic field strength. Thus, for electric thruster plumes, cyclotron radiation does not pose a problem for space telescope systems. However, it might cause radio frequency interference for the electronics onboard or possible future radio frequency telescopes.

C. Blackbody Radiation

All objects above *absolute zero* temperature will emit radiation corresponding to their temperature and emissivity. The power per unit area per unit wavelength of this emission, called blackbody radiation, will be given by Planck's formula:

$$R(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \tag{10}$$

Assuming that no component of the parent spacecraft or no nearby flying spacecraft get in the field of view of the collector mirrors, the thermal (blackbody) radiation due to surfaces can be ignored. However, such radiation emission has to be looked into when the scattering effects are taken into account.

D. Scattering Processes

Regardless of where the spacecraft orbit is located, there will be some ambient or reflected radiation that might get scattered off the plume plasma particles and get collected by the telescope system. For a spacecraft in an orbit around the sun, the main source of radiation will be the radiation from the sun itself. For a spacecraft in an orbit around a celestial object, in addition to the direct solar radiation, the reflected radiation from celestial body's atmosphere has to be taken into account. In addition, blackbody thermal emission from the warm surfaces of the spacecraft might get scattered to the field of view of the telescopic system. Such processes require a comprehensive examination and are left for another study.

IV. Discussion on Radiation Collection

For a thruster located on a spacecraft, the plume particles expand according to the pressure and electromagnetic forces acting on them. Collisions between particles and the particle interactions with the spacecraft surfaces play an important role in the expansion process. The plume plasma particles get into the field of view of the telescopes by direct expansion of the plume towards the telescope's field of view and by the scattering of particles into the field of view due to collisional interactions between the particles and with the surfaces. Taking above mentioned mechanisms into consideration, expansion of Hall thruster plumes are modeled using a hybrid-PIC DSMC plume plasma simulation code. Obtained numerical simulation results of the plume plasma environment around the formation flying TPF interferometer spacecraft for a hypothetical firing scenario were presented at an earlier study.[1] In this section, we present the preliminary results of the radiation emission collection by the TPF collectors for the same scenario.

A. Collection Criteria

The field of view angle, φ, of a telescope will be the main determining factor in deciding the criteria for detection of radiation due to thruster plume particles. A schematic picture of the field of view for the TPF-I collector spacecraft is shown in Fig. 3. A plume plasma particle will be seen by the collector if its distance from the telescope axis $b < D/2 + \frac{\varphi}{2}d$ where D is the diameter of the primary mirror, d is the axial distance of the particle from the telescope and φ is the field of view angle.[12] This collection zone is schematically presented in Fig. 4.

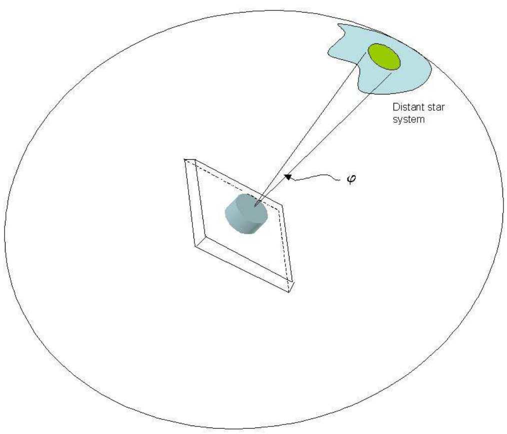

Figure 3. TPF collector field of view, φ

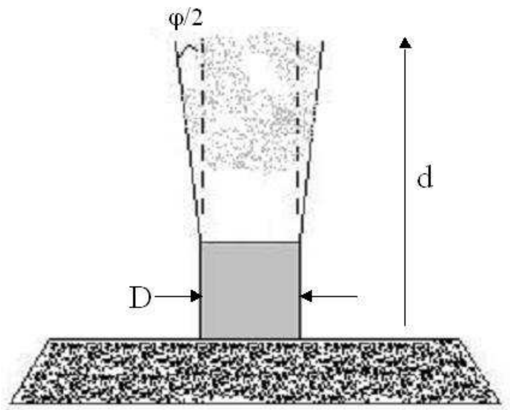

Figure 4. TPF radiation collection zone

However, not all the radiation reaching the collector mirrors will be detected. The collector mirrors reflect radiation that has a parallel wavefront within the limits of the field of view angle and focuses it onto the detector. So for those particles that radiate within the volume described in Fig. 4, only a fraction corresponding to the solid angle given by the field of view angle will be detected. For TPF-I, with a field of view of 1 arcsecond, only a ratio given by

$$Detection\ Ratio = \frac{\frac{\pi}{4}\varphi^2}{4\pi} = \frac{\frac{\pi}{4}(1\ arcsec)^2}{4\pi} = 1.47 \times 10^{-12} \tag{11}$$

of the radiation emitted by the plume particles will be focused onto the detector and affect the observed signal.

B. Sample TPF Radiation Contamination Study

In order to asses the thruster plume radiation contamination effects for the formation flying TPF interferometer, a computational study was conducted using a hybrid-PIC plume model, AQUILA. Even though the TPF-I architecture is composed of five formation-flying spacecraft as depicted in Fig. 5, only two neighboring collector spacecraft with the least separation distance are modeled. This is where the expected thruster-spacecraft interactions are the greatest. A view of the computational mesh used in this study is shown in Fig. 6. The mesh that encloses both spacecraft has a size of about $50m \times 35m \times 25m$. The spacing between the spacecraft is $18m$ corresponding to interferometer baseline length of $\sim 100m$. Two BHT-200 Hall thrusters are placed at the corners of one of the collector spacecraft and are simultaneously fired in the direction of the adjacent collector spacecraft.

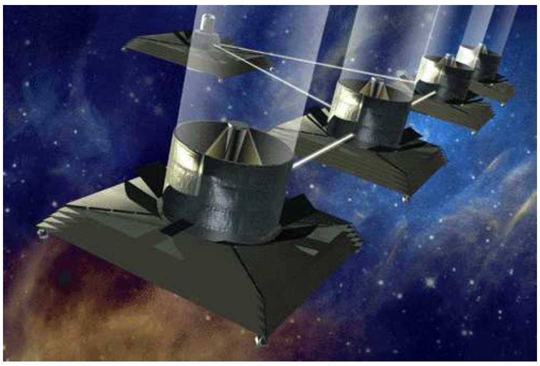

Figure 5. Artist's conception of TPF-I spacecraft[13]

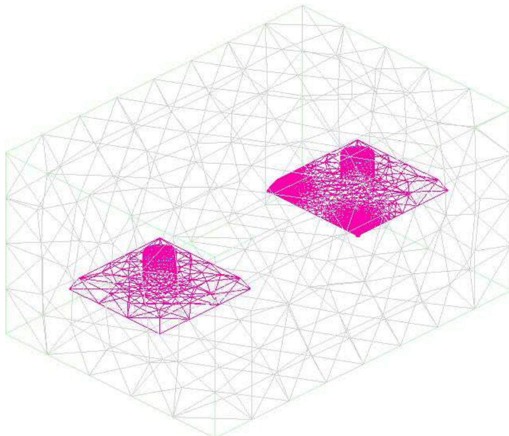

Figure 6. Computational mesh for 2 TPF-I spacecraft

Due to the availability of limited excitation cross-section data, radiation caused by only 20 prominent XeI and XeII emission lines in the visible and near-IR wavelength range were modeled along with the continuum emission due to Bremsstrahlung processes for the IR wavelength range of $1 - 21\mu m$. Using the appropriate collection zone and detection criteria arguments introduced earlier in this section, the plume radiation intensity detected by the TPF-I system is obtained by the simulation. For the calculations, the plume plasma is assumed to be optically thin.

According to the results, assuming a spectral resolution $\lambda/\Delta\lambda = 20$, corresponding to an average collection bin wavelength range of about half a micron, the number of photons collected per second due to plume plasma Bremsstrahlung radiation emission is $\sim 5 \times 10^{-8}$ for the $12\mu m$ wavelength bin. Since, the expected radiation flux from an earth-like planet at 33 light years away is 0.25 photons per second at $12\mu m$, then the interference due to Bremsstrahlung radiation emission would be orders of magnitude lower than the expected signal from the planet.[14]

Due to lack of experimental data, no line emission in the mid-IR wavelength range is modeled. However the results of the modeled visible-NIR radiation emission give clues about the expected interference effects of possible mid-IR line radiation. For this study 4 XeI visible, 8 XeI near-IR, and 8 XeII visible line emissions are modeled using the experimental excitation cross section values provided by Karabadzhak et al.[6] Due to low density and low electron temperature of the plume plasma in the field of view region, the intensity of the detected line radiation is very low in comparison to the observed signal. As an example, number of photons collected by the telescope system for XeI 467.1 nm line emission would be on the order of 10^{-18} photons per second, which is orders of magnitude lower than the expected signal from the observed planet. Since, most of the reported mid-IR transitions for noble gases are magnetic dipole (M1) or electric quadrupole (E2) transitions, the intensity of the expected mid-IR radiation emission would be even less than that of the visible or near-IR emission.

V. Conclusion

For space telescope projects, one major area of concern is the contamination of the observed signal due to the emission from the thruster plume particles. For electric thrusters, with Xenon plasma plumes, several plume radiation emission processes are discussed. The detection of the plume radiation emission by space telescopes has been investigated. Preliminary results of numerical studies of the detection of electric thruster plume emission by the formation flying Terrestrial Planet Finder collector spacecraft were presented.

Acknowledgments

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