# Role of suprathermal runaway electrons returning to the acceleration region in solar flares


Meriem Alaoui, Gordon Holman, Joel Allred, Rafael Eufrasio

NASA Goddard Space Flight Center, Solar Physics Laboratory, Code 671, Greenbelt, MD 20771, USA; Department of Physics, The Catholic University of America, Washington, DC 20064, USA University of Arkansas, Fayetteville, AR, 72701, USA


## How do return currents affect observations?

(1) They heat the flaring corona, they can reduce the fration of electrons reaching the chromosphere

(2) They flatten the hard X-ray spectra at lower energies if the potential drop is high enough

(3) Upward-propagating suprathermal electrons can be observed in radio emission

## Method

(1) Determine the electric field strength as a function of position along loop for which the return current (RC) balances the nonthermal beam current $J_{RC}=-J_{beam}$ and $J_{RC}=J_{drift}+J_{runaway}$

(2) Runaway growth rates are well-defined for weak electric field strengths compared to Dreicer field (less than ~0.1 Ed). Use this to calculate the runaway current

## Main result

Three regimes of the return current explain the dynamics of the beam/return-current transport.

We derive these ranges for combinations of the injected flux density+ temperature & density along a loop:

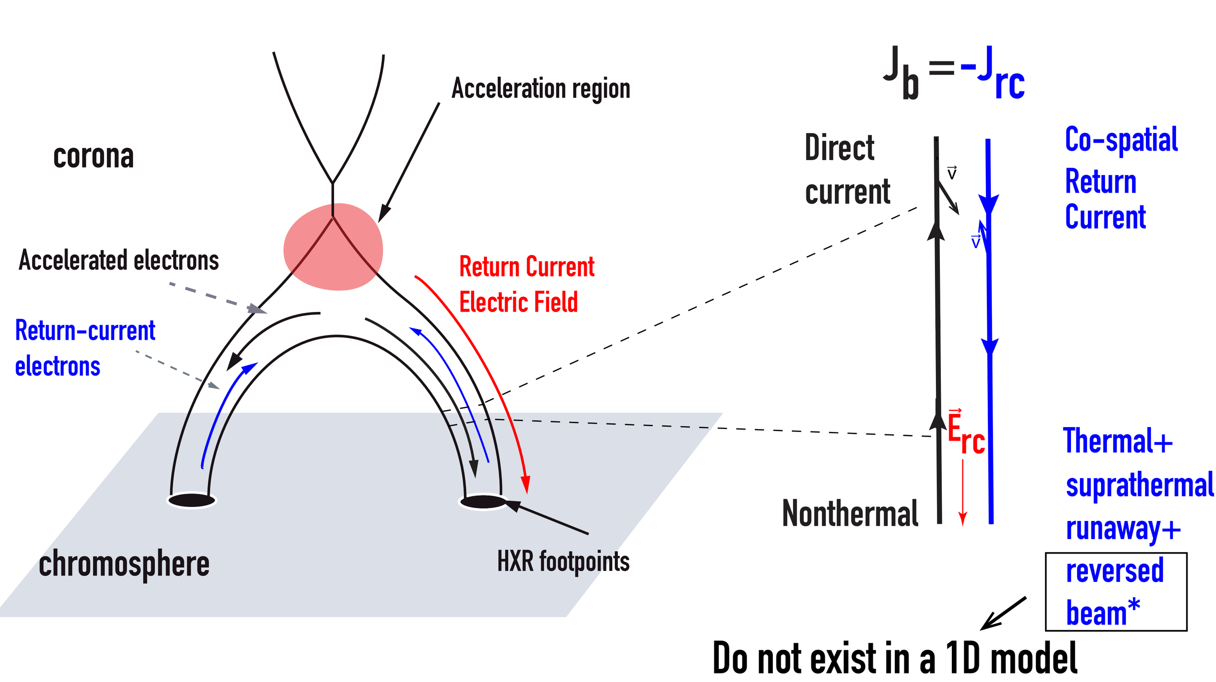
(1) For lower injected flux densities, Ohm's law accurately describes the system,

(2) For medium range flux densities, runaway electrons become significant: They reduce the heating, reduce the HXR flattening and return suprathermal electrons to the acceleration region

(3) For higher flux densities either the RC is dominated by runaways (purely runaway regime, most likely), this further reduces the coronal heating and the HXR flattening; or current-driven instabilities produce a higher effective resistivity therefore a higher heating rate in the corona, and stronger flattening at lower energies of the observable HXR spectrum (deka-keV range).

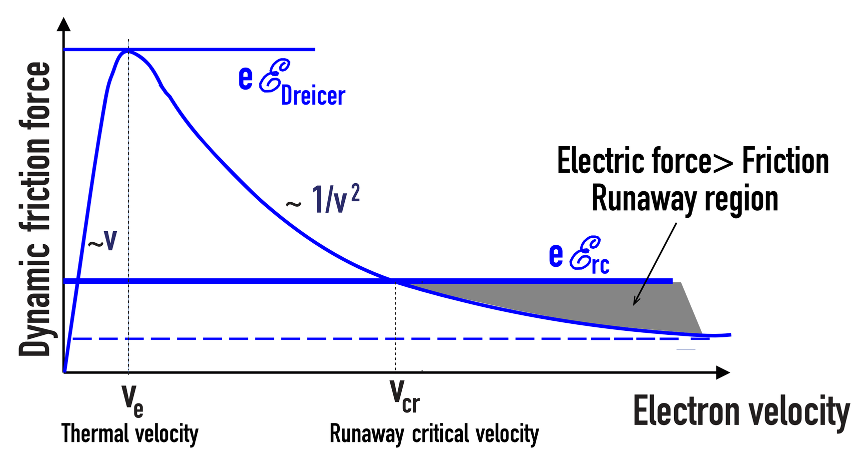
## Nonthermal Beam/Return-Current (RC) Runaway Model

Fig 1: Cartoon of co-spatial return-current model. Electrons are accelerated above-the-looptop and propagate downward. Within a collision time [a,b] the return current electric field is established and the beam current is balanced by the co-spatial return current. The induced magnetic field by the beam is canceled by that of the return current. For higher electric field magnitudes, more runaways are accelerated out of the RC plasma.



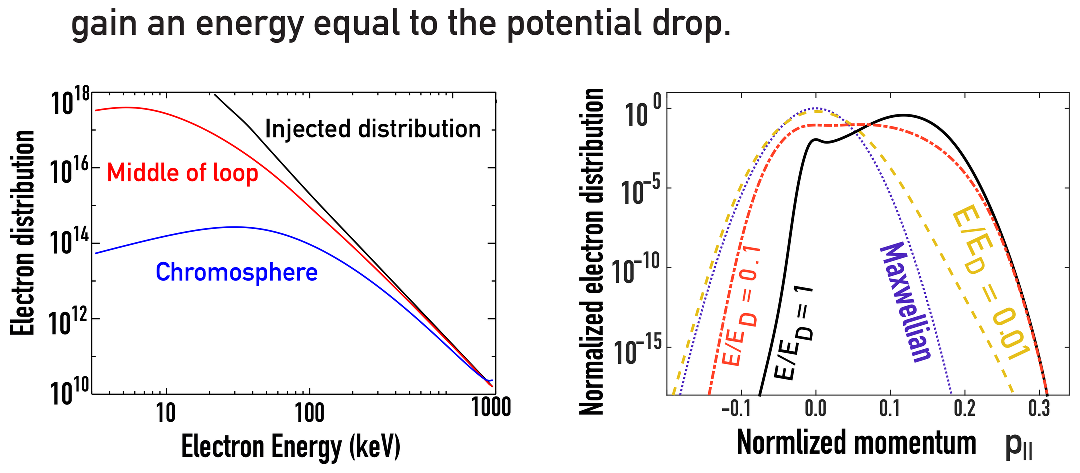

## Runaway electrons

Fig 2: Schematic of friction force as a function of electron velocity. When the electrical force exceeds the friction, electrons are freely accelerated and therefore Ohm's law does not apply to them.




## Schematic nonthermal beam and RC distributions

Fig 3: Schematic distributions of beam and RC. **Left:** As beam electrons are decelerated by the RC electric field and Coulomb collisions along the loop, the distribution flattens. In the chromosphere, Coulomb collisions dominate. **Right:** The higher the normalized electric field, the more runaways are accelerated. As they propagate toward the looptop they gain an energy equal to the potential drop.




Right: Adapted from Stahl et al 2017

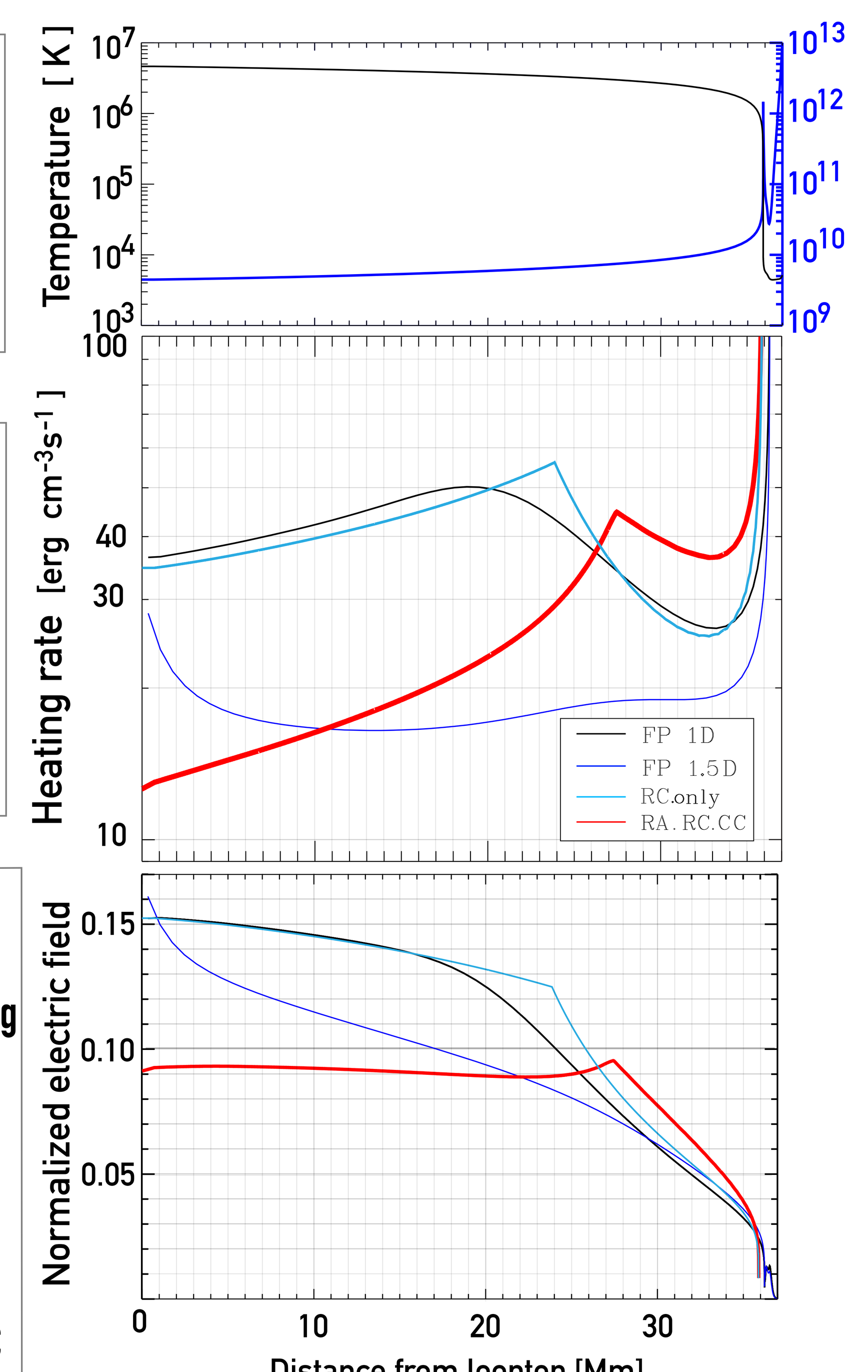
## Runaway electrons reduce heating in corona by reducing the electric field

Fig 4: Atmosphere in which the beam is injected. Four models are used for comparison. Heating rate in the upper corona is lowest when runaways are accounted for (RA.RC.CC). The sharp decrease in the heating rate is due to thermalization of lower energy electrons.

Example of a solar atmosphere in which nonthermal beam is injected

Heating rate using four different models. Only RA.RC.CC includes runaways and has lowest heating rate in upper corona

Electric field is reduced+beam electrons start being thermalized lower in loop when runaways are considered (RA.RC.CC) because beam RC losses are reduced

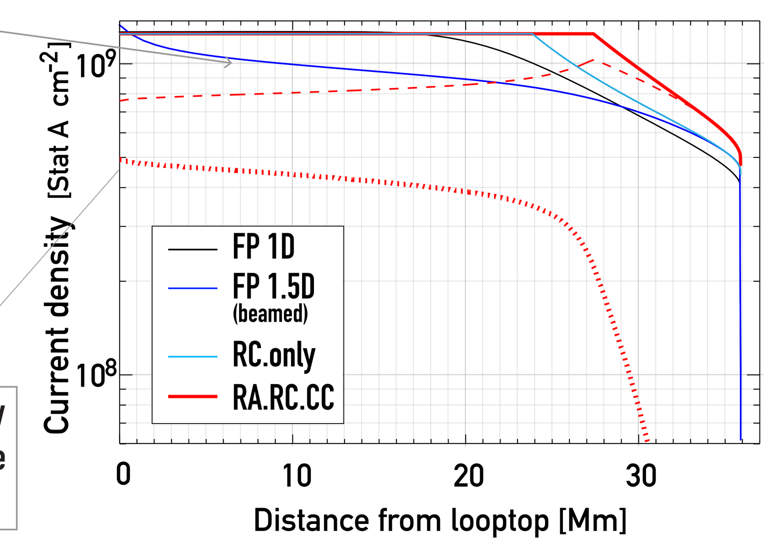



## Suprathermal runaway electrons return to the looptop

Fig 5: Current density using four models. In all models the beam current and RC densities are balanced along the loop. In the runaway model we further show the runaway and drifting components of RC.

1.5 D FP initially beamed model loses downward electrons first through pitch-angle scattering

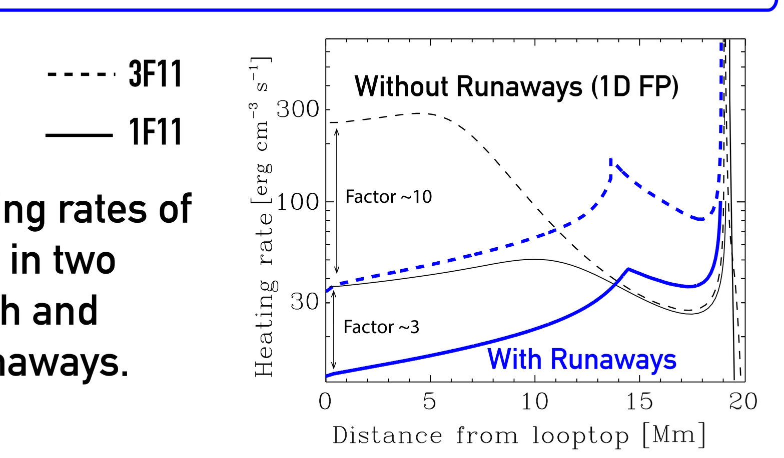
39% of flux density at looptop is in the runaway regime




Thermalization of lower energy beam electrons happens at different heights. In the runaway model the electrons lose the least energy and therefore the thermalization distance is closer to the chromosphere.

## Self-reducing effect of runaways

Fig 6: Heating rates of two beams in two models with and without runaways.



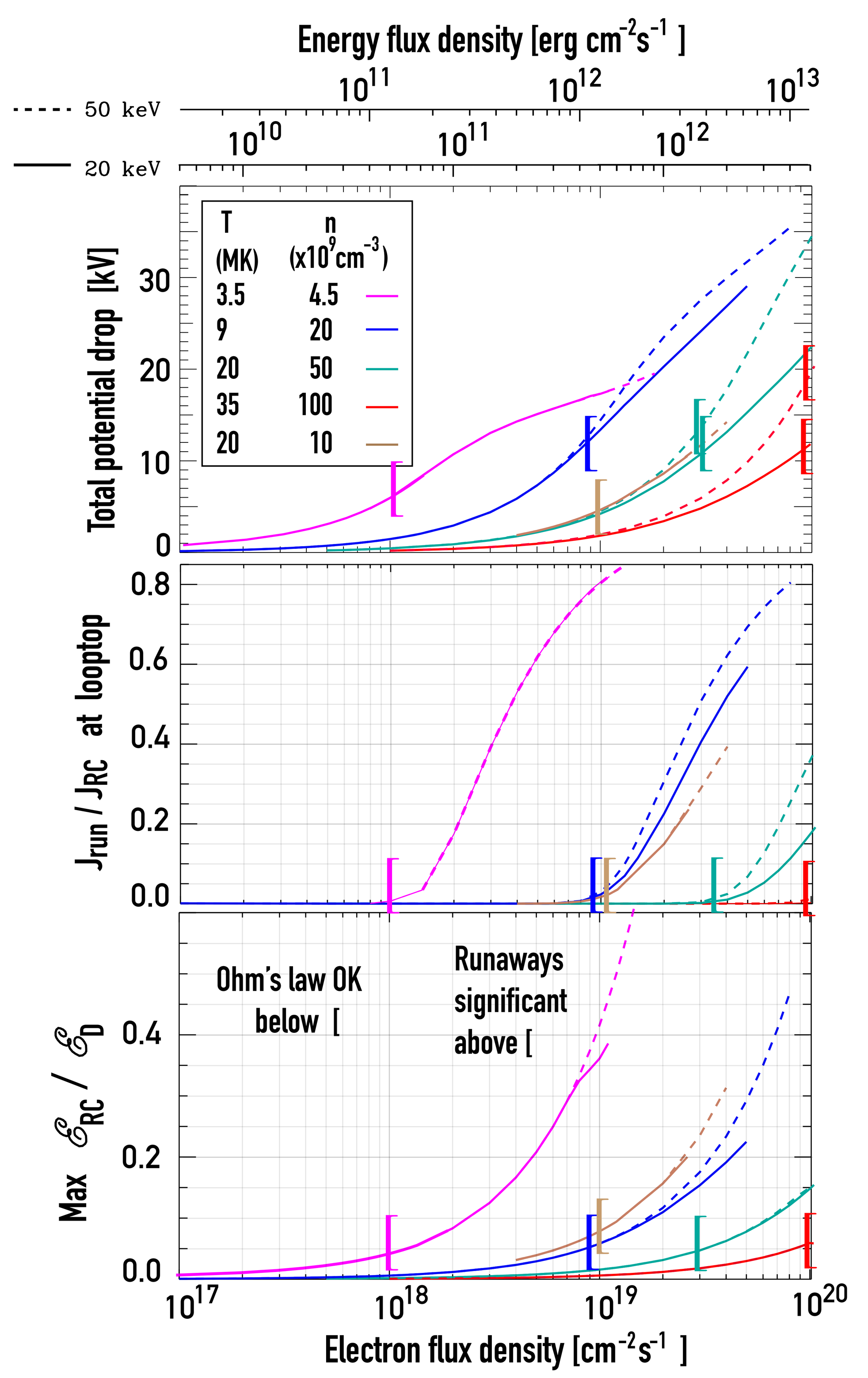

A higher injected flux density generates a higher electric field thereby accelerating more runaways.

Therefore a higher reduction of the electric field and a higher reduction of the heating rate is associated with higher injected flux densities

## Beam flux densities where runaways become significant

Fig 9: Total potential drop (top), runaway current fraction at the looptop (middle), and maximum normalized RC electric field (bottom). For the injection of beams with δ= 4 into the atmospheres listed in the top panel.

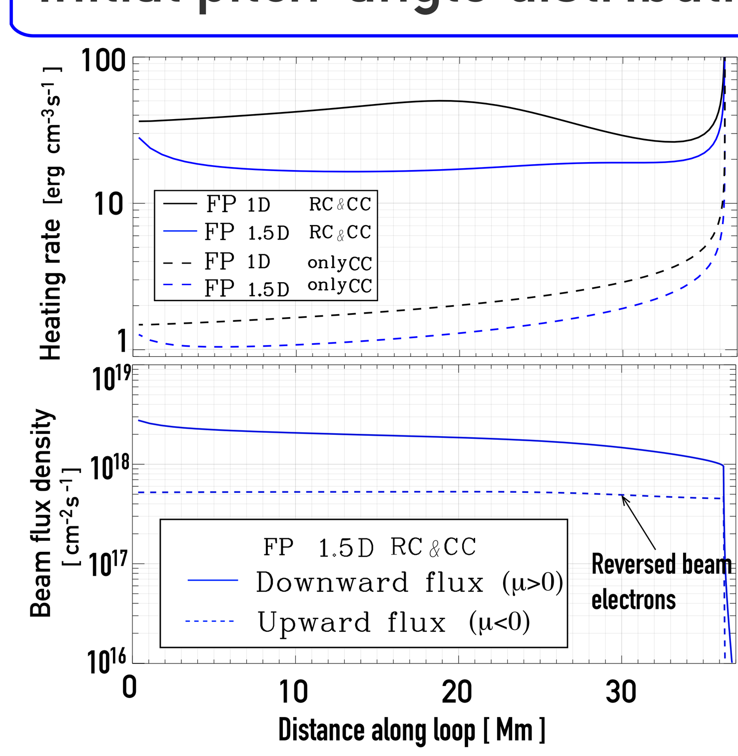
Our solutions for Max $E_{RC}/E_D$>>0.1 are only qualitatively correct.




For low enough flux densities, i.e. below the symbol "[", Ohm's law governs the return-current dynamics.

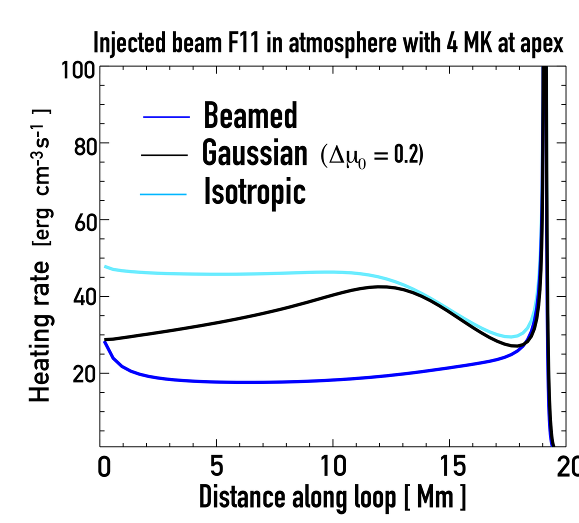
For higher flux densities injected into the various atmospheres, runaways become significant in reducing the heating rate in the corona and the HXR flattening at lower energies. In addition, these suprathermal runaways return to the acceleration region, where they can be further accelerated.

## Initial pitch-angle distribution also affects heating & nonthermal electrons at looptop




Runaways accelerated out of the ambient plasma are not the only suprathermal electrons that return to the acceleration region. Beam electrons can be back-scattered or/and reversed by the electric field (also see Karlicky 1993, Siversky & Zharkova 2009, Zharkova & Dobranski 2016).

We use the Fokker-Planck code of Allred et al. 2020. This code is similar to Zharkova & Gordovskyy 2006 with the addition of the full collisional terms similarly to Jeffrey et al. 2014 and Kontar et al. 2015. The main effects are that (1) lower energy electrons are thermalized higher in the corona, thereby reducing the electric field and heating below the thermalization distance and (2) a much smaller fraction of reversed electrons reaches the looptop.




## References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meriem.alaouiabdallaoui@nasa.gov