ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2018) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Review

Physics of meteor generated shock waves in the Earth's atmosphere – A review

Elizabeth A. Silber [a,*], Mark Boslough [b], Wayne K. Hocking [c], Maria Gritsevich [d,e,f], Rodney W. Whitaker [g]

[a] Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA
[b] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA
[c] Department of Physics and Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada
[d] Department of Physics, University of Helsinki, P.O. Box 64, FI-00014, Finland
[e] Institute of Physics and Technology, Ural Federal University, Ekaterinburg, Russia
[f] Dorodnicyn Computing Centre, Russian Academy of Sciences, Moscow, Russia
[g] Los Alamos National Laboratory, EES-17 MS F665, P.O. Box 1663, Los Alamos, NM 87545, USA

Received 12 February 2018; received in revised form 25 April 2018; accepted 8 May 2018

Abstract

Shock waves and the associated phenomena generated by strongly ablating meteoroids with sizes greater than a few millimeters in the lower transitional flow regime of the Earth's atmosphere are the least explored aspect of meteor science. In this paper, we present a comprehensive review of literature covering meteor generated shock wave phenomena, from the aspect of both meteor science and hypersonic gas dynamics. The primary emphasis of this review is placed on the mechanisms and dynamics of the meteor shock waves. We discuss key aspects of both shock generation and propagation, including the great importance of the hydrodynamic shielding that develops around the meteoroid. In addition to this in-depth review, the discussion is extended to an overview of meteoroid fragmentation, followed by airburst type events associated with large, deep penetrating meteoroids. This class of objects has a significant potential to cause extensive material damage and even human casualties on the ground, and as such is of great interest to the planetary defense community. To date, no comprehensive model exists that accurately describes the flow field and shock wave formation of a strongly ablating meteoroid in the non-continuum flow regime. Thus, we briefly present the current state of numerical models that describe the comparatively slower flow of air over non-ablating bodies in the rarefied regime. In respect to the elusive nature of meteor generated shock wave detection, we also discuss relevant aspects and applications of meteor radar and infrasound studies as tools that can be utilized to study meteor shock waves and related phenomena. In particular, infrasound data can provide energy release estimates of meteoroids entering the Earth's atmosphere. We conclude with a summary of unresolved questions in the domain of meteor generated shock waves; topics which should be a focus of future investigations in the field.

Keywords: Meteor; Shock wave; Meteoroid; Cylindrical shock wave; Shock physics; Meteor radar

* Corresponding author at: Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook St., Box 1846, Providence, RI 02912, USA.
E-mail addresses: elizabeth_silber@brown.edu, esilber@uwo.ca (E.A. Silber).

https://doi.org/10.1016/j.asr.2018.05.010
0273-1177/

Please cite this article in press as: Silber, E.A., et al. Physics of meteor generated shock waves in the Earth's atmosphere – A review. Adv. Space Res. (2018), https://doi.org/10.1016/j.asr.2018.05.010

Nomenclature

List of variables

a	accommodation coefficient
A_s	the dimensionless shape factor for a specific meteoroid shape
c	speed of sound
C	specific heat of the meteoroid
C_D	drag coefficient
d	diameter, blunt object
d_m	diameter, meteoroid
E	energy
E_{vapor}	energy, ablated vapor
h	altitude
k	Boltzmann constant
Kn	Knudsen number
Kn_v	Knudsen number within vapor cap
m	mass, meteoroid
M_∞	Mach number
m_a	mass, air molecule
m_m	mass, meteoric molecule/atom
M_{sw}	Mach number, shock wave
N_v	the number of vaporizing meteoric molecules/atoms
p	pressure, shock
p'	pressure behind compression shock
p_0	pressure, ambient atmosphere
p_1	pressure, free stream
p_2	pressure, shock
Q	latent heat of vaporization
R_0	blast (or characteristic) radius
r_0	radius, initially formed meteor trail
Re	Reynolds number
r_m	radius, meteoroid
S	projected cross-sectional area
T	temperature
T'	temperature behind compression shock
T_0	temperature, ambient air
T_m	mean temperature, meteoroid
T_s	temperature, meteoroid surface
t	time
v	meteoroid velocity (or velocity of the air stream over the meteoroid)
$\bar{v}_v$	mean velocity of the reflected/evaporated atoms and molecules from the meteoroid surface, and ahead of the shock wave
V_m	volume, meteoroid
V_1	volume, upstream flow
V_2	volume, shock
v_1	flow velocity, free stream
v_2	flow velocity, shock
$v_{particles}$	velocity, vapor cloud molecules
x	distance traveled by a blunt body
γ	specific heat ratio
δ	shock detachment distance
ε	emissivity of the meteoroid
Λ	heat transfer coefficient (heat of ablation of the meteoroid material)
μ	dynamic viscosity coefficient
ρ	density
ρ'	density behind compression shockρ_0 density, ambient atmosphere
ρ_1	density, free stream
ρ_2	density, shock
ρ_a	density, air
ρ_m	density, meteoroid
σ_a	ablation coefficient
σ_{SB}	Stefan-Boltzmann constant
τ_c	characteristic time, chemical reactions
τ_f	characteristic time, for a fluid element to travel the distance of the flow field
Φ	Mach cone angle
h	enthalpy per unit mass
h_0	total enthalpy per unit mass
h_1	enthalpy per unit mass, undisturbed flow
h_2	enthalpy per unit mass, shock
$\boldsymbol{k}$	thermal conductivity
M_i	molar mass of species (i)
p	pressure
p_1	pressure, undisturbed flow
p_2	pressure, shock layer
$\boldsymbol{q_R}$	radiative heat
T	temperature
T_1	temperature, undisturbed flow
T_2	temperature, shock layer
u, v, w	components of velocity $\boldsymbol{V}$
$\boldsymbol{U}_i$	velocity of the ith species in the flow field
$\boldsymbol{V}$	velocity (vector form), flow field
v_1	velocity, undisturbed flow
v_2	velocity, shock layer
λ	bulk viscosity coefficient
μ	dynamic viscosity coefficient
ρ	density
ρ_1	density in undisturbed flow
ρ_2	density, shock layer

Please cite this article in press as: Silber, E.A., et al. Physics of meteor generated shock waves in the Earth's atmosphere – A review. Adv. Space Res. (2018), https://doi.org/10.1016/j.asr.2018.05.010