Radiative Cooling
New Opportunities & Enabling Technologies

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An opportunity to tap an underutilized resource

Use the cold of outer space to radiatively pump heat from the ground through sky access

New: Possible at all hours of the day through photonic design of thermally emissive layers

Meaningful cooling power that scales with area: analogies to PV
Radiative cooling is enabled by an atmospheric transparency window between 8 – 13 μm.

Blackbody spectrum of typical Earth temperature objects overlap with window.

Varies with cloud cover, geographic location and ozone pollution.
Power balance equation

\[ P_{net}(T) = P_{rad}(T) - P_{atm}(T_{amb}) \]
The need for *selective* thermal emission

\[ P_{net}(T) = P_{rad}(T) - P_{atm}(T_{amb}) \]

**Hemispherical integrals:**

\[ P_{rad}(T) \propto I_{BB}(T, \lambda)\varepsilon(\lambda, \theta) \]

\[ P_{atm}(T_{amb}) \propto I_{BB}(T_{amb}, \lambda)\varepsilon(\lambda, \theta)\varepsilon_{atm}(\lambda, \theta) \]

Thermal emissivity is not a fixed number:

It can be engineered by *photonic design*

Emissivity of radiating surface

Emissivity of atmosphere

Hemispherical sky access for maximal cooling power
The potential of an ideal selective emitter

I. INTRODUCTION

Radiative cooling is a technique that exploits a natural transparency window for electromagnetic waves in the Earth's atmosphere to transport heat from terrestrial objects into cold space. As a result, objects with the appropriate radiative properties can passively cool themselves down to temperatures well below the ambient. The atmospheric transparency window is found in the 8-13 \( \mu m \) wavelength range, as shown in Fig. 1, and fortuitously overlaps with the blackbody spectral radiance corresponding to typical terrestrial temperatures (0-50°C), thus enabling objects at these temperatures to emit more power than they absorb.

Prior work in radiative cooling has almost entirely focused on nighttime cooling, where one aims to maximize emission in the atmospheric transparency window, without having to contend with solar radiation. In turn, nighttime cooling is of limited practical relevance since solar radiation is by far the greatest source of daytime heating. Early work on nighttime cooling mainly focused on choosing the right materials and exploiting simple interference effects. Granqvist et al. theoretically investigated and characterized the properties of the ideal nighttime radiator, finding that such radiator could reach nighttime temperatures which were 50°C lower than the ambient, with a cooling power of 100 W/m² when the radiator temperature was 20°C.
Potential of an ideal selective emitter

Effective of parasitic ambient heating when below air temperature:

\[ P_{\text{nonrad}} = h_c \Delta T \]
Radiative Cooling at Night: Experimental Data

The challenge during the day

Daytime Radiative Cooling Surface

Sun: 6000 K
Earth objects: 300 K

$T^4$ intuition:

Cooling demand peaks during the day:

Can we achieve meaningful cooling then?
Simultaneously emit thermal radiation and reflect sunlight strongly

Temperature [K] (T_{ambient} = 300K)

Ideal selective emitter

Selective + 3% solar absorption
Selective + 5%
Selective + 10%
Photonic design enables daytime radiative cooling

Achieve desired thermal emissivity by photonic design

Overcome material limitations

Benefits & challenges of radiative cooling

Passive (electricity-free) cooling powers of \( \sim 30-90 \text{ W/m}^2 \) to drop temperatures 5-10°C below ambient.

With advanced photonic design, available at all hours of the day.

Operating costs limited to maintenance and pumping energy.

Can work in the hottest (and even humid) days.

Can be additive to other cooling mechanisms.

Inherently large-area.

Geometrical constraints: flat surface with access to full sky hemisphere ideal.

Atmospheric constraints: performance can drop by 1/2 if cloudy/rainy.

Efficient packaging needed to ensure minimal parasitic losses to the ambient.

Maximal benefit available at night.
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