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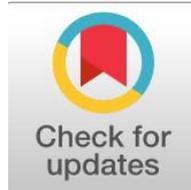How to submit to this journal (link)

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Recent Progress in the Characterization of the Atmosphere of Exoplanets: Observations, Models

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Abstract

General Background: Characterizing exoplanet atmospheres has become a major focus of modern astrophysics to understand the composition, structure, and evolution of planets beyond the Solar System. **SpecificBackground:** Advancesinobservationalinstruments,spectroscopytechniques,and atmospheric modeling especially with next-generation telescopes such as the James Webb Space Telescope have expanded the capability to study planetary atmospheres. **Knowledge Gap:** However, challenges remain in interpreting atmospheric spectra due to retrieval degeneracies, stellar contamination, and limitations in cloud and chemical modeling. **Aims:** This review summarizes recent developments in observational techniques and atmospheric analysis used in exoplanet research. **Results:** Recent observations have detected molecules such as H_2O, CO_2, CH_4, Na, K, and SO_2, while improved spectroscopic methods allow investigation of atmospheric circulation, thermal structure, disequilibrium chemistry, and atmospheric escape. **Novelty:** The study integrates recent observational and modeling progress that advances atmospheric characterization techniques. **Implications:** These developments support deeper understanding of planetary diversity and strengthen the search for habitable environments and biosignatures beyond Earth.

Highlights:

• Multi-method spectroscopic observations reveal molecular composition and atmospheric structure of distant planets.
• Next-generation telescopes provide broader wavelength coverage enabling detection of trace gases.
• Modern retrieval algorithms integrate machine learning and radiative transfer modeling for spectral interpretation.

Keywords: Exoplanet Atmospheres, Atmospheric Spectroscopy, James Webb Space Telescope, Transmission Spectroscopy, Planetary Science

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1. Introduction

Exoplanet science Since the discovery of the first exoplanet around a main-sequence star in 1995, the science of exoplanets has since shifted away from the detection phase and into the characterization phase. Atmospheric research is the new frontier of this discipline, as it has the capability of determining chemical composition, thermal structure, and processes that take place in the alien worlds. The study of the atmospheres of exoplanets is critical to answer some of the key questions of astrophysics, such as the formation, migration, habitation, and abundance of life outside the Earth [1-3].

Between 2020 and 2025, the field experienced transformative growth due to:

- Better space-based observatories.
- Terrestrial -high-resolution spectroscopy.
- Retrieval techniques with machine learning support.
- More realistic radiative transfer models.

This review provides the synthesis of recent developments and is critical of observational and theoretical developments.

2. Techniques of Characterizin g the Atmosphere by Observation

2.1 Transmission Spectroscopy

Transmission spectroscopy is a technique which determines the wavelength-dependent absorption of starlight upon passing through the atmosphere of a planet as it transits through the atmosphere. Such recent developments include:

Atmospheric scale heights: Measurement of atmospheric scale heights.

JWST has greatly enhanced spectral resolution and wavelength range (0.6-28 μm) making it possible to detect trace gases that were previously impossible [4-6].

2.2 Emission and Eclipse Spectroscopy

Depends on light and radiation that enables the identification of an unknown. Planetary thermal emission is enclosed by secondary eclipse observations. The major milestones of 2020 have been:

- Water vapor, CO_2, CH_4, SO_2, etc.
- Connotation of clouds and hazes.
- Retrieval of temperature pressure profile.
- Things that thermal inversions will be detected.
- Measurement of redistribution efficiency of heat.

Jupiter of ultra-hot temperature exhibit signs of molecular breaching of chemistry and recombination [7,8].

2.3 Direct Imaging

Direct imaging isolates planetary light from stellar glare using coronagraphs and adaptive optics. Recent successes include [8,9]:

- Spectra of young giant planets
- Measurement of atmospheric metallicity
- Detection of silicate clouds

2.4 High-Resolution Spectroscopy

Ground-based spectrographs now achieve resolving power >100,000. Advantages [9,10]:

- Detection of individual molecular lines
- Measurement of wind speeds
- Doppler mapping of atmospheric circulation

3. Atmosp heric Chemistry and Composition

3.1 Molecular Detections

Recent observations have proved the existence of:

Molecule	Significance
H_2O,	Indicator of atmospheric structure
CO_2,	Key carbon cycle tracer
CH_4,	Possible biosignature

Na, K	Trace alkali metals
SO_2,	Photochemical processes

JWST observations revealed unexpected sulfur chemistry in several hot Jupiter atmospheres, challenging equilibrium chemistry models [10].

3.2 Disequilibrium Chemistry

The processes of disequilibrium involve:

- Photochemistry
- Vertical mixing
- Atmospheric escape

These processes can generate spectral signatures that are not consistent with equilibrium predictions, and these processes can only be modeled with complicated models [11,12].

4. Clouds and Hazes

It is important to note that clouds are dramatic factors in spectral interpretation by blotting absorption features. Recent progress includes:

- Silicate and iron clouds identification.
- Modelling of particle size distribution.
- Three-dimensional steady-state global circulation calculation.

Formation of clouds seems to be in relation to the equilibrium temperature and metallicity [13].

5. Important Retriev al Techniques in the atmosphere

Inverse modeling in Retrieval techniques is a technique that retrieves atmospheric properties based on spectra [14].

5.1 Bayesian Retrieval

Modern retrieval codes employ [14,15]:

- Nested sampling algorithms
- Markov Chain Monte Carlo (MCMC)
- Machine learning accelerators

5.2 Degeneracy Challenges

Parameter degeneracies arise between [16]:

- Temperature vs. composition
- Cloud opacity vs. molecular abundance
- Stellar contamination vs. planetary signal

Recent approaches combine multi-wavelength datasets to reduce uncertainties.

6. Escape and Evolution of the Atmosphere

The point of atmospheric escape is significant in the development of the planets. Observations show [16,17]:

- Hydrogen escape of hot Neptuns.
- The absorption of helium is an indicator.

Escape processes include:

- Mass-loss rates up to 10^{11} g/s.
- Hydrodynamic escape
- Stellar wind stripping
- Photoevaporation

7. Habitability and Biosignatures

7.1 Habitable Zone Atmospheres

Habitable planets are the best targets. Most important biomarkers that are being investigated:

O_2, O_3, CH_4, and N_2O [16]

7.2 False Positives

Biosignatures may be imitated by Abiotic processes. Examples:

- Photolysis producing O_2
- Volcanism generating CH_4
- Stellar activity which changes spirits.

This means that life can only be detected with the use of multi-gases [17].

8. James Webb Space Telescope Role

JWST is the revolution that has transformed characterization of the atmosphere by [17,18]:

- Sensitivity An observation of molecules at an unprecedented sensitivity.
- Expanding spectral range to mid- infrared.
- Observing smaller planets

It was found out that:

- CO_2 in sub-Neptune atmospheres.
- Photochemical products are found in hot Jupiter.
- Evidence of metallic clouds.

9. Current Challenges

Despite rapid progress, several obstacles remain [18]:

Challenge	Impact
Stellar activity	Contaminates spectra
Instrument systematics	Limits precision
Cloud modeling	Introduces degeneracy
Signal-to-noise limits	Restricts small-planet detection

10. Discussion

The last five years can be seen as a shift of exoplanet atmosphere science in the direction of precision astrophysics rather than exploratory science. Observational data combined with the use of sophisticated models has changed the focus of attention to simple detection to the characterization. Nevertheless, the solution of degeneracies, enhancement of signal accuracy, and the host star variability still are important steps to go [18,19].

The interdisciplinary work between astronomers, chemists, atmospheric scientists and data scientists is becoming more important. Machine learning will become a common method of retrieval and classification [19,20].

11. Conclusion

The characterization of the exoplanet atmospheres has entered a revolutionary era brought by the technological inventions and theoretical developments. The compositional and structural studies of distant worlds have been made possible due to observational breakthroughs, especially the JWST ones. In spite of the difficulties, current methodological advances, and the prospective observation telescopes will reveal the diversity of planets, the physics of their atmospheres and the possibility of life-bearing planets beyond the Earth in ways never before seen. It is believed that the next decade will see a shift to the direct detection of atmospheres to the relative exoplanet climatology and biosignature validation.

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