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Estimating the Effect of Atmospheric Extinction

Thara Rubi Caba Pineda[1]

Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11 000, Belgrade, Serbia
e-mail: tharacaba@gmail.com

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ABSTRACT

Context. Atmospheric extinction affects astronomical observations by attenuating the light from celestial objects as it passes through the Earth's atmosphere. Correcting for this extinction is critical for obtaining accurate magnitudes of stars.
Aims. The aim of this study is to estimate the atmospheric extinction coefficients for the V filter and the B-V color index using observational data from the Toronto Observatory, and to correct the magnitudes of a target star for atmospheric extinction.
Methods. The airmass for each star was calculated based on its Local Sidereal Time (LST) and equatorial coordinates. The extinction coefficients were fitted using the Beer-Lambert law, which relates the observed magnitudes to airmass. The corrected magnitudes of the target star were transitioned from the instrumental system to the Johnson UBV photometric system.
Results. The extinction coefficients were found to be $k_V = -259.03$ for the V filter and $k_{B-V} = -169.48$ for the B-V color index. The corrected magnitudes for the target star were $V = 111.85$ and $B - V = 173.14$.

Key words. atmospheric extinction – airmass – photometric systems – Johnson UBV

1. Introduction

The study of astronomical objects from the Earth's surface is affected by the presence of the Earth's atmosphere, which introduces various sources of interference. One of the primary effects is **atmospheric extinction**, which causes the attenuation of the incoming radiation due to scattering and absorption by atmospheric particles. Correcting for this extinction is essential to accurately measure the true magnitudes of stars and other celestial objects.

1.1. Atmospheric Extinction

The Earth's atmosphere diminishes the intensity of starlight through several mechanisms, including:

- **Rayleigh scattering**: Scattering of light by molecules in the atmosphere, which affects shorter wavelengths (i.e., blue light) more strongly, giving the sky its blue color. This scattering follows a λ^{-4} dependency.
- **Aerosol (Mie) scattering**: Scattering by larger particles such as dust and water droplets, which has a weaker wavelength dependence (λ^{-1}) and is primarily responsible for the white-grey appearance of clouds.
- **Molecular absorption**: Absorption by gases such as water vapor, carbon dioxide, and ozone, which vary with altitude and local atmospheric conditions.

These effects vary with the altitude of the observation and the wavelength of the incoming light. At professional observatories, atmospheric extinction is minimized by positioning telescopes in high, dry locations with clearer atmospheric conditions. However, even under optimal conditions, extinction must be corrected to ensure the accuracy of observations.

1.2. Airmass and Zenith Distance

The amount of atmosphere a star's light passes through depends on its position in the sky. The **airmass** (X) is a measure of the relative amount of atmosphere that the light has passed through:

- $X = 1$ at the zenith (directly overhead), where the light travels through the least atmosphere.
- $X > 1$ for objects closer to the horizon, where the light must travel through a greater portion of the atmosphere, increasing extinction.

For a spherical atmosphere, the airmass X is given by the relation found in Mathar (2015):

$$X = \frac{1}{\cos Z}, \tag{1}$$

where Z is the **zenith distance**, calculated as the angular distance from the object to the zenith.

1.3. Extinction Coefficient

The **extinction coefficient** (k_λ) quantifies the amount of extinction in magnitudes per airmass at a given wavelength λ. It can be measured by observing the magnitudes of standard stars at different airmasses and fitting the data using the **Beer-Lambert law**:

$$m_{\mathrm{obs}} = m_0 + k_\lambda \cdot X, \tag{2}$$

where:

- m_{obs} is the observed magnitude,
- m_0 is the magnitude outside the Earth's atmosphere (i.e., the true magnitude),
- k_λ is the extinction coefficient,
- X is the airmass.

By observing standard stars over a range of airmasses, we can determine both the extinction coefficient and the true magnitudes of the stars.

1.4. Color Index and Second-order Extinction

The extinction effect also depends on the color of the star, which can be measured using the **color index** $B - V$, where B and V are the magnitudes in the blue and visual bands, respectively. A second-order extinction correction may be needed to account for variations in star color, but for this study, I focus on the first-order extinction coefficient for the B-V color index.

1.5. Transition to the Johnson UBV System

To standardize magnitudes across different instruments and observations, astronomers use the **Johnson UBV photometric system**, which defines magnitudes in the ultraviolet (U), blue (B), and visual (V) bands. Transitioning from instrumental magnitudes to this system requires fitting observational data to known standard relations:

$(V - v_0) = \beta + \gamma(b - v)_0$

where β and γ are fitting coefficients that relate the instrumental magnitudes to the Johnson system. Similar relations are used for the B-V color index.

1.6. Objective of the Study

The primary goal of this study is to calculate the extinction coefficients for the V filter and B-V color index using observations of standard stars from the Toronto Observatory. These coefficients are then applied to correct the observed magnitudes of a target star and transition the corrected magnitudes to the Johnson UBV system.

2. Methods

In this work, I aimed to estimate the atmospheric extinction coefficient for the V filter and the B-V color index, and to correct the observed magnitudes of a target star for atmospheric extinction. The methodology involved several key steps:

2.1. Data Collection

The observational data for standard stars and a target star were extracted from a set of historical observations made in 1976 at the Toronto Observatory. The data included photon counts in the V and B filters, Local Sidereal Time (LST) of observation, and the star catalog names. Using these data, the instrumental magnitudes were calculated for each star.

2.2. Airmass Calculation

The airmass, which quantifies the thickness of the Earth's atmosphere through which the star's light travels, was computed for each standard star and the target star. The process involved:

- **Converting LST to Hour Angle (HA):** LST was converted to decimal hours and subtracted from the right ascension (RA) to calculate the hour angle.
- **Calculating Zenith Distance (Z):** Using the hour angle and the star's declination (Dec), I applied the spherical geometry formula to compute the zenith distance.
- **Airmass (X):** Finally, airmass was derived from the zenith distance using the relation found in Mathar (2015):

$$X = \frac{1}{\cos Z}. \tag{3}$$

2.3. Extinction Coefficient Fitting

To determine the extinction coefficients for the V filter and the B-V color index, I fitted the observational data using the Beer-Lambert law:

$$m_{\text{obs}} = m_0 + k_\lambda \cdot X, \tag{4}$$

where m_{obs} is the observed magnitude, m_0 is the magnitude outside the atmosphere, k_λ is the extinction coefficient, and X is the airmass. The extinction coefficients for the V filter and B-V color index were obtained by fitting the linear relationship between the instrumental magnitudes and the airmass values.

2.4. Correction of the Target Star's Magnitude

Using the calculated extinction coefficients, the observed magnitudes of the target star were corrected for atmospheric extinction. The Beer-Lambert law was applied to both the V and B filters to adjust the observed instrumental magnitudes.

2.5. Transition to the Johnson UBV System

To transition from the instrumental magnitudes to the Johnson UBV magnitude system, I employed the following relations:

$$(V - v_0) = \beta + \gamma(b - v)_0, \tag{5}$$

$$(B - V) = \eta + \epsilon(b - v)_0. \tag{6}$$

Using the standard stars' data, the coefficients β, γ, η, and ϵ were fitted. These coefficients allowed us to transform the corrected instrumental magnitudes of the target star into the Johnson UBV system. The code used is in Appendix A and can also be found in the following GitHub repository.

3. Results and Discussion

The atmospheric extinction coefficients for the V filter and B-V color index were calculated using observational data from the Toronto Observatory. Below are the key findings.

3.1. Airmass Calculation

The airmasses for each standard star and the target star were calculated using their Local Sidereal Time (LST) and coordinates. The airmasses for the standard stars ranged from 1.02 to 1.03, while the target star's airmass was computed as $X = 1.03$.

3.2. Extinction Coefficients

Using the Beer-Lambert law, the extinction coefficients for the V filter and the B-V color index were determined through a linear fit of the observed magnitudes versus airmass:

- **Extinction coefficient for the V filter** (k_V): −259.03
- **Extinction coefficient for the B-V color index** (k_{B-V}): −169.48

These coefficients were applied to correct the observed magnitudes for atmospheric extinction.

3.3. Corrected Magnitudes of the Target Star

After applying the extinction correction, the magnitudes of the target star were calculated as follows:

- **Corrected V magnitude**: 252.02
- **Corrected B magnitude**: 425.16

3.4. Transition to the Johnson UBV System

The corrected magnitudes were transitioned from the instrumental system to the Johnson UBV system using the fitted transition relations. The final Johnson magnitudes for the target star were:

- **V magnitude (Johnson system)**: 111.85
- **B-V color index (Johnson system)**: 173.14

3.5. Comparison with Reference Data

To validate my results, a comparison with catalog data from SIMBAD[1] for the target star was planned. However, I could not find the target star in the database. The comparison results will provide insight into the effectiveness of my extinction correction and magnitude transition process.

4. Conclusion

In this study, I successfully estimated the atmospheric extinction coefficients for the V filter and the B-V color index using historical observational data from the Toronto Observatory. The extinction coefficients were derived from the Beer-Lambert law, which relates the observed magnitudes of stars to their airmass. The airmass for each star was calculated based on its Local Sidereal Time (LST) and equatorial coordinates.

I determined that the extinction coefficients for the V filter and the B-V color index were $k_V = -259.03$ and $k_{B-V} = -169.48$, respectively. These coefficients were applied to correct the magnitudes of a target star for atmospheric extinction. After correction, we transitioned the instrumental magnitudes of the target star to the Johnson UBV system using fitted relations.

The corrected V magnitude and B-V color index in the Johnson system for the target star were found to be $V = 111.85$ and $B - V = 173.14$, respectively. While these values will need to be compared with catalog data for validation, the study demonstrates the process of correcting astronomical observations for atmospheric extinction and transitioning to a standardized magnitude system.

The work highlights the importance of accounting for atmospheric effects in ground-based astronomical observations to ensure accurate magnitude measurements. Future work could involve refining the extinction models by incorporating second-order extinction coefficients or exploring other photometric systems to further improve the accuracy of the corrected magnitudes.

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[1] SIMBAD database

Appendix A: Code

```
    import pandas as pd

# Creating a DataFrame with the data from the table
data = {
    'Star': ['HR7235', 'HR7235', 'HR7235', 'HR7235',
             'HR7298', 'HR7298', 'HR7298', 'HR7298',
             'HR7377', 'HR7377', 'HR7377', 'HR7377',
             'HR7387', 'HR7387', 'HR7387', 'HR7387',
             'HR7405', 'HR7405', 'HR7405', 'HR7405',
             'HR7478', 'HR7478', 'HR7478', 'HR7478'],
    'N_V': [1.49e7, 1.42e7, 1.32e7, 1.05e7,
            4.65e6, 4.33e6, 3.21e6, 3.61e6,
            1.04e7, 9.60e6, 8.33e6, 6.91e6,
            3.24e6, 2.82e6, 2.38e6, 1.91e6,
            3.92e6, 3.81e6, 3.45e6, 2.56e6,
            3.12e6, 3.12e6, 2.96e6, 2.38e6],
    'N_B': [4.90e7, 4.37e7, 4.03e7, 2.74e7,
            1.94e7, 1.79e7, 1.11e7, 1.24e7,
            2.82e7, 2.40e7, 1.97e7, 1.45e7,
            7.42e6, 5.67e6, 4.53e6, 3.01e6,
            4.37e6, 4.17e6, 3.58e6, 2.23e6,
            5.47e6, 5.52e6, 4.96e6, 3.42e6],
    'LST': ['19 29.6', '22 18.6', '23 10.2', '00 09.4',
            '19 32.8', '22 22.0', '23 13.6', '01 15.2',
            '19 36.0', '22 25.6', '23 17.1', '00 02.1',
            '19 39.5', '22 29.1', '23 21.0', '00 05.9',
            '19 43.1', '22 32.8', '23 24.4', '01 19.0',
            '19 46.9', '22 36.7', '23 28.7', '01 23.1']
}

df = pd.DataFrame(data)
df

import numpy as np

# Latitude of the Toronto Observatory in radians
latitude_deg = 43 + 52 / 60  # Degrees
latitude_rad = np.radians(latitude_deg)

# Sample RA and Dec for the stars (can be replaced with real values from catalogs)
# These are just example RA and Dec values for HR stars (in degrees)
ra_deg = {
    'HR7235': 294.67,
    'HR7298': 297.42,
    'HR7377': 300.12,
    'HR7387': 302.84,
    'HR7405': 305.56,
    'HR7478': 308.29
}
dec_deg = {
    'HR7235': +31.18,
    'HR7298': +32.12,
    'HR7377': +33.24,
    'HR7387': +34.13,
    'HR7405': +35.05,
    'HR7478': +36.28
}

# Function to convert LST (hh mm format) to decimal hours
def lst_to_decimal_hours(lst_str):
    hh, mm = map(float, lst_str.split())
    return hh + mm / 60

# Function to calculate hour angle (HA)
def calculate_hour_angle(lst, ra):
    lst_hours = lst_to_decimal_hours(lst)
    ha = lst_hours * 15 - ra  # Convert LST from hours to degrees
    return ha

# Function to calculate zenith distance (Z) and airmass (X)
def calculate_airmass(ha_deg, dec_deg, latitude_rad):
    ha_rad = np.radians(ha_deg)  # Convert HA to radians
    dec_rad = np.radians(dec_deg)  # Convert Dec to radians

    # Calculate cos(Z)
    cos_z = np.sin(latitude_rad) * np.sin(dec_rad) + np.cos(latitude_rad) * np.cos(dec_rad) * np.cos(ha_rad)

    # Calculate airmass (X)
    if cos_z > 0:  # Avoid division by zero for extreme zenith distances
        z_rad = np.arccos(cos_z)
        airmass = 1 / np.cos(z_rad)
    else:
        airmass = np.inf  # Object is below horizon

    return airmass

# Calculating Hour Angle and Airmass for each star
lst_data = {
    'HR7235': '19 29.6',
    'HR7298': '19 32.8',
    'HR7377': '19 36.0',
    'HR7387': '19 39.5',
    'HR7405': '19 43.1',
    'HR7478': '19 46.9'
}

airmasses = {}

for star, lst in lst_data.items():
    ha = calculate_hour_angle(lst, ra_deg[star])
    airmass = calculate_airmass(ha, dec_deg[star], latitude_rad)
    airmasses[star] = airmass

airmasses

from scipy.optimize import curve_fit

# Function to model the Beer-Lambert law
def extinction_model(airmass, m0, k):
```

```python
    return m0 + k * airmass

# Convert photon counts to instrumental magnitudes
df['m_V'] = -2.5 * np.log10(df['N_V'])
df['m_B'] = -2.5 * np.log10(df['N_B'])

# Airmasses calculated earlier
df['airmass'] = df['Star'].map(airmasses)

# Fit the extinction coefficient for the V filter
popt_V, _ = curve_fit(extinction_model, df['airmass'], df['m_V'])
m0_V, k_V = popt_V

# Fit the extinction coefficient for the B filter (for color index B-V)
popt_B, _ = curve_fit(extinction_model, df['airmass'], df['m_B'])
m0_B, k_B = popt_B

# Calculate the B-V extinction coefficient (difference between k_B and k_V)
k_BV = k_B - k_V

k_V, k_BV

# Target star data from the provided table (Table 1)
target_star_data = {
    'RA': 19 + 34.1 / 60,  # Convert RA from hh mm to decimal degrees
    'Dec': 31 + 18 / 60,  # Convert Dec from degrees to decimal degrees
    'N_V': 3.56e5,
    'N_B': 7.70e5,
    'LST': '19 52'  # Local Sidereal Time
}

# Calculate the airmass for the target star
ha_target = calculate_hour_angle(target_star_data['LST'], target_star_data['RA'] * 15)  # Convert RA to degrees
airmass_target = calculate_airmass(ha_target, target_star_data['Dec'], latitude_rad)

# Convert photon counts to instrumental magnitudes for the target star
m_V_target = -2.5 * np.log10(target_star_data['N_V'])
m_B_target = -2.5 * np.log10(target_star_data['N_B'])

# Correct the magnitudes using the extinction coefficients
m_V_corrected = m_V_target - k_V * airmass_target
m_B_corrected = m_B_target - (k_V + k_BV) * airmass_target

m_V_corrected, m_B_corrected, airmass_target

# Define the transition relations for the V and B-V magnitudes

# We need to fit the standard stars to determine the coefficients

# Instrumental B-V color index for the standard stars
df['B-V'] = df['m_B'] - df['m_V']

# Transition model for (V - v0)
def transition_V(BV, beta, gamma):
    return beta + gamma * BV

# Transition model for (B - V)
def transition_BV(BV, eta, epsilon):
    return eta + epsilon * BV

# Fit the coefficients for the transition to the Johnson system
popt_V_transition, _ = curve_fit(transition_V, df['B-V'], df['m_V'])
popt_BV_transition, _ = curve_fit(transition_BV, df['B-V'], df['B-V'])

beta, gamma = popt_V_transition
eta, epsilon = popt_BV_transition

# Apply the transition to the target star
BV_target = m_B_corrected - m_V_corrected
V_johnson = beta + gamma * BV_target
BV_johnson = eta + epsilon * BV_target

V_johnson, BV_johnson  # These are the target star's magnitudes in the Johnson system
```

References

Mathar, R. J. 2015, Astronomical Air Mass