# 大气湍流理论的进展及其天文学意义

侯 金 良
(中国科学院上海天文台 上海 200030)

**摘 要**

传统的大气湍流理论始于大约 30 年前. 湍流理论的发展使得天文学家对大气湍流对天文观测的影响有了很好的认识, 尤其是它为天文台选址和天文高分辨率技术提供了基础. 近年来新的天文观测已对传统的大气湍流理论提出了挑战, 并可能给地面天文观测带来一场革命. 在回顾了大气湍流理论的发展历史后对传统大气湍流理论的基本特性及其应用作了系统的综述, 并介绍了新的天文观测事实以及为此而提出的新的大气湍流理论模型.

**关 键 词** 大气效应 — 湍流 — 选址

# The Development of Atmospheric Turbulence Theory and Its Impact on Ground-based Astronomical Observation

Hou Jinliang
(*Shanghai Astronomical Observatory, The Chinese Academy of Sciences, Shanghai* 200030)

(*Received 1996 March 8*)

## Abstract

Conventional atmospheric turbulence theory was well developed approximately 30 years ago. Good knowledge of the effects of atmospheric turbulence on astronomical observation has been obtained by astronomers because of the development of turbulence theory. Particularly, the theory provides the basis of site selection and high resolution techniques for astronomy. In recent years, new images recorded by large and high quality telescopes have resulted in some difficulties in conventional image formation theory. The new phenomenon, if confirmed, may give rise to a revolution in ground-based astronomy. In this paper, the history of turbulence theory is reviewed, the main characteristics of atmospheric turbulence and its application are summarized. Finally, a brief discussion about new observational phenomenon as well as new atmospheric turbulence theory are given.

**Key words** atomospheric effects—turbulence—site testing

---

1996 年 3 月 8 日收到

# 1 Introduction

One of the main obstacles in ground-based optical astronomy is the atmospheric turbulence since it greatly reduces the angular resolution of the telescope. For this, astronomers are continuously seeking for the ways of overcoming it. The early Michelson interferometer and current space telescope are those examples. Meanwhile, the nature of atmospheric turbulence as well as the image formation theory through the turbulence are also being studied extensively by both astronomers and atmospheric physicists.

In 1961, the mechanisms of wave propagation in a turbulent medium were well reviewed by Tatarski[1], and a conventional theory of atmospheric turbulence based on the $-5/3$ Kolmogorov energy spectrum law of turbulence was established. Shortly after Tatarski's review, Hufnagel and Stanley[2] developed equations for the atmospheric modulation transfer function(MTF) in terms of the atmosphere's structure constants. They also described the intensity distribution in the image of an unresolved star by Fourier transformation of the transfer function. Soon afterward, Fried[3,4] presented expressions for describing the long-exposure and short-exposure resolution limits that the atmosphere imposes on a telescope. Fried first introduced a parameter $r_0$, called atmospheric coherence length or Fried parameter, or seeing parameter, which is widely accepted as the characteristic quantity of atmospheric turbulence. At the same time, growing interest in laser beam propagation through the atmosphere further fueled the development of atmospheric turbulence and imaging theory[5−9]. The introduction of speckle interferometry in 1970 by Labeyrie[10] made it possible for full use of telescope aperture, which widened the interest in the properties of short-exposure images formed by large telescope. The conventional theory has been most efficiently applied since 1980's because of the need of selecting a good site for new generation large ground-based telescopes. A detailed discussion about this has been given by Roddier[11].

Generally speaking, the theoretical results are consistent with the real situation under the conditions of astronomical observations. Astronomers can now not only measure the properties of atmospheric turbulence but also establish some models to predict the seeing condition making the observation more effective[12,13,14,15].

In the early 1990's, British astronomer Griffin expressed his doubt about the conventional atmospheric turbulent theory[16]. His observational experiences made him believe that the better the telescope optics, the more often can a star light be concentrated in an image core determined by the diffraction limit of a telescope instead of the seeing. In order to explain this observational phenomenon, a different atmospheric model has been developed by McKechnie[17,18]. The primary point is the assumption of finite turbulent outer scale which was supposed to be infinite in the conventional theory. In fact, finite outer scale has been measured by both atmospheric physicists and astronomers[19,20,21]. Secondly, the layered atmosphere was replaced by a large number of statistically independent random phase screen distributed throughout the height of the atmosphere. The phase screen was described by a wave height function, whose statistical properties determine the modulation function and spectral correlation function of the turbulent atmosphere. Compared with the conventional theory, this wave height function actually corresponds to the atmospheric coherent length parameter. Generally, it is possible to explain the observed core-halo structure with this new theory. If the new predictions are confirmed, a revolution in ground-based astronomy could lie just ahead. The new generation 8–10 meter optical and infrared telescopes would routinely produce diffraction limited cores in long-exposure images as long as they are constructed from precise optical specifications.

Although there are arguments between supporters of new model and the conventional theory[22,23], the increasing observational evidence makes it necessary for astronomers to make much effort to the properties of turbulent atmosphere.

## 2 Basic Parameters of Atmospheric Turbulence and Its Importance

### 2.1 Atmospheric coherence length–spatial coherence

The spatial correlation function of atmospheric turbulence is given by[11]

$$B(\boldsymbol{\xi}) = \exp\{-3.44(|\boldsymbol{\xi}|/r_0)^{5/3}\}, \tag{1}$$

where $r_0$ is Fried parameter, also called atmospheric coherence length. It is related to the structure constant of refractive index $C_N^2(h)$ by the following equation

$$r_0 = \{0.423(2\pi/\lambda)^2 \sec z \int_0^\infty C_N^2 \mathrm{d}h\}^{-3/5}, \tag{2}$$

where $\lambda$ is the wavelength and $z$ is the zenith angle.

The parameter $r_0$ is now a widely accepted "figure of merit" for atmospheric seeing quality. It determines the angular resolution of a ground-based telescope. The angular diameter, also called "seeing angle", of the image recorded by a telescope with diameter $D$ is of the order of $1.27\lambda/r_0$. For short-exposure as in the speckle mode, the number of speckles in a speckle image is proportional to $(D/r_0)^2$.

### 2.2. Atmospheric coherence time–spatial-temporal coherence

In short-exposure imaging, the evolution properties of the wavefront perturbation determine the optimal exposure time for recording the best image(speckle interferogram). This temporal parameter can be described by the spatial-temporal coherence function $B_\tau(\boldsymbol{\xi})$. Assuming the layer distribution of turbulence, $B_\tau(\boldsymbol{\xi})$ can be written[11]

$$B_\tau(\boldsymbol{\xi}) = \exp\left\{-3.44 r_0^{-3/5} \frac{\int |\boldsymbol{\xi} - \tau \boldsymbol{v}(h)|^{5/3} C_N^2(h)\mathrm{d}h}{\int C_N^2(h)\mathrm{d}h}\right\}. \tag{3}$$

If we define a decay function $\sigma(\tau)$ as

$$\sigma(\tau) = \int B_\tau^2(\boldsymbol{\xi})\mathrm{d}\boldsymbol{\xi}, \tag{4}$$

then it can be approximated to

$$\sigma(\tau) \simeq \sigma(0)\exp\{-6.88(\Delta V)^2(\tau/r_0)^2\}, \tag{5}$$

where $\sigma(0) = 0.342(r_0/\lambda)^2$ is the coherence area, $\Delta V$ is the dispersion in altitude of the atmospheric horizontal wind speed weighted by the turbulence strength. We have the 5/3 replaced by 2 before getting equation (5).

From equation (5), the coherence time can be calculated using

$$\Delta\tau \simeq 0.38r_0/\Delta V, \tag{6}$$

which is defined as the value of $\tau$ when $\sigma(\tau)$ reduces to $e^{-1}$.

Aime *et al.* found the $\Delta\tau \simeq 0.47r_0/\Delta V$ under the assumption that the autocorrelation function may have a Lorentzian shape instead of a Gaussian shape[24]. The two expressions are in good consistency.

The $\Delta\tau$ is an important atmospheric parameter since it approximately describes the longest possible exposure time for recording speckle interferograms. It is also an essential quantity for testing atmospheric condition at existing and future sites of astronomical observations. It can be derived from space-time correlation functions of single star speckle interferograms[24–30]. Its typical value is about 2–30 ms.

### 2.3. Isoplanatic angle–spatial-angles coherence

When light wave passes through the atmosphere, the temporal perturbation of wavefront within a certain angle will be coherent. This is so-called isoplanatic property of the atmospheric turbulence. The size of this angle is called isoplanatic angle. For extended objects imaging, it becomes important to know the dependence of wavefront perturbations on the direction of observation. This dependence is described by the spatial-angular coherence function $B_\theta(\boldsymbol{\xi})$[11]

$$B_\theta(\boldsymbol{\xi}) = \exp\left\{-3.44r_0^{-3/5}\frac{\int|\boldsymbol{\xi}-\theta h|^{5/3}C_N^2(h)\mathrm{d}h}{\int C_N^2(h)\mathrm{d}h}\right\}. \tag{7}$$

With the similar treatment, we can get the isoplanatic angle $\theta$ by

$$\theta \simeq r_0/\Delta h, \tag{8}$$

where $\Delta h$ is the dispersion of turbulence altitudes weighted by the turbulence strength.

Isoplanatic angle plays an important role in speckle holography and in adaptive optics. It can be derived from the cross-correlation functions of speckle patterns produced by the two components of the double star[30]. Its typical size is 2–6 arcsec.

### 2.4. Spectral coherence

In interferometric measurements, the spectral coherence puts limits on the bandwidth. It can be defined as the correlation between wavefront perturbation at two different wavelengthes[31]

$$B(\lambda_1,\lambda_2)=\exp\{-3.44(\frac{\Delta\lambda}{\lambda})^2(\frac{L}{r_0})^{5/3}\},\qquad (9)$$

where $L$ is the baseline length, $\Delta\lambda=\lambda_1-\lambda_2$, $\lambda\simeq\lambda_1\simeq\lambda_2$.

When coherence drops to $e^{-1}$, we have

$$\frac{\Delta\lambda}{\lambda}=0.45(r_0/L)^{5/6}.\qquad (10)$$

The above analysis demonstrate that $r_0$ is the basic parameter of describing atmospheric turbulence. A large value of $r_0$ is preferable for astronomical observations. Table 1 summarizes the dependence of various parameters on the wavelength and zenith angle.

**Table 1 Summary of the Parameters for the Atmospheric Turbulence**

| Parameter | Expression | $k1$ in $\lambda^{k1}$ | $k2$ in $(\cos z)^{k2}$ | Typical value |
|---|---|---|---|---|
| Fried parameter $r_0$ | | 6/5 | 6/5 | 10 – 30 cm |
| coherence time $\tau$ | $r_0/\Delta V$ | 6/5 | 3/5 | 5 – 30 ms |
| isoplanatic angle $\theta$ | $r_0/\Delta h$ | 6/5 | 8/5 | 2 – 6 arcsec |
| seeing angle $\omega$ | $1.27\lambda/r_0$ | −1/5 | −3/5 | 1 arcsec |
| coherence area $\sigma$ | $0.34(r_0/\lambda)^2$ | 12/5 | 6/5 | |
| no. of speckles $N$ | $2.3(D/r_0)^2$ | −12/5 | −6/5 | |
| max. bandwidth $\Delta\lambda/\lambda$ | $0.45(r_0/L)^{5/6}$ | 1 | 1/2 | |

# 3 The Effect of Atmospheric Turbulence on Astronomy

## 3.1 FWHM

One of the basic parameters of judging the quality of an image is its Full Width of Half Maximum(FWHM). It can be related to the atmospheric coherence length by using modulation transfer function(MTF).

According to the image formation theory, when a telescope records a star image, the intensity profile in the focal plane is the inverse Fourier transform of the system MTF, that is

$$P(\boldsymbol{\nu})=\int\tau(\boldsymbol{f})\exp(i2\pi\boldsymbol{\nu}\cdot\boldsymbol{f})\mathrm{d}\boldsymbol{f}.\qquad (11)$$

Because of the axial symmetry, the Fourier transform can be replaced by the Hankel transform. This leads to

$$P(\rho)=2\pi\int_0^{D/\lambda}\tau(f)J_0(2\pi\rho f)f\mathrm{d}f,\qquad (12)$$

where $J_0$ is the zero-order Bessel function, $\rho$ the image radius, $D$ the telescope diameter.

Let $\xi=\lambda f/D$, $r=\rho\frac{r_0}{\lambda}s$, and $s=D/r_0$, then

$$P(r) = 2\pi(\frac{r_0}{\lambda})^2 D^2 \int_0^1 \tau(\xi) J_0(2\pi r \xi)\xi \mathrm{d}\xi. \tag{13}$$

The MTF of a system is given by

$$\tau(f) = T(f)B(f), \tag{14}$$

where $T(f)$ is the telescope MTF, $B(f)$ the atmospheric MTF. For long-exposure imaging, it can be written as[11]

$$B(f) = \exp\left\{-3.44(\frac{\lambda f}{r_0})^{5/3}\right\}. \tag{15}$$

If $D = \infty$, that is $T(f) = 1$, then we can get

$$\mathrm{FWHM} \simeq 0.976\frac{\lambda}{r_0}. \tag{16}$$

If the telescope is diffraction limited, the result is shown by curve $A$ in Fig. 1.

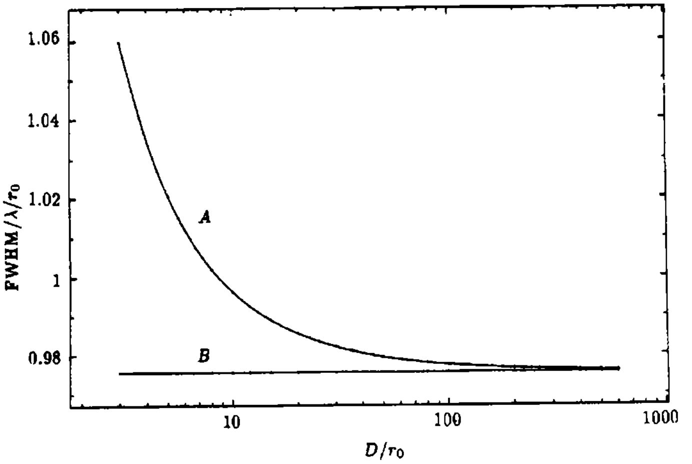


Fig.1 The dependence of FWHM on $D/r_0$ (see text for details)

When the telescope is not perfect, Dierickx concluded that under the assumption of third-order spherical aberration, the FWHM is not very sensitive to wavefront errors introduced by the telescope itself[23].

### 3.2 The performance of telescope facilities

In order to overcome the influence of atmospheric turbulence on ground-based telescope, most of the telescopes are equipped with high angular resolution instrument, such as speckle interferometer and adaptive optics. The limiting performance of those instruments are greatly affected by atmospheric seeing quality.

Generally, the limiting magnitude of the telescope is proportional to $r_0^k$, where $k$ is about 3 to 5 depending on the high angular resolution terminal used[31,33]. In adaptive optics, the number of necessary subapertures $N$ is given by $(D/r_0)^2$. The less the $N$, the cheaper and easier for construction of the system.

It is obvious that the limiting performance is very sensitive to seeing parameter. From this, we see that good site selection is essential for large ground-based optical and infrared telescopes.

### 3.3 Image motion theory and its application

The image quality of a ground-based telescope is degraded by the transmission of light from the astronomical objects through the turbulent atmosphere of the Earth. The reason for this degradation is a random spatial and temporal wavefront perturbation induced by the turbulence in the different layers of the atmosphere. For large ground-based telescopes, the image is blurred and spread since the wavefront across the aperture is not coherent. However, the central position of the image is stable because of the spatial and temporal average of the wavefront direction.

For small telescope, on the other hand, the situation is different. In this case, the short-exposure image will be perfect since the wavefront across the aperture is coherent. For long-exposure, the image position will tremble, and the locus of its center of gravity will be spread in a disk. The diameter of the disk is about the size of an image formed by large telescope. When the telescope is in medium size, the result will be the combination of blurring and motion.

Let $\sigma$ be the rms image motion (in $\lambda/D$ units) , the MTF representing the image motion is [11]

$$P(f) = \exp(-2\pi^2\sigma^2 f^2). \tag{17}$$

If we define the resolution power of the optical system as the integration of MTF, that is

$$R = \int \tau(f)\mathrm{d}f, \tag{18}$$

and the equivalent area of the MTF was regarded as that of a uniform lighted disk with angular diameter $\alpha$, then

$$(\frac{\pi}{4})\alpha^2 = R^{-1}. \tag{19}$$

Since the MTF has different expression for different imaging situation, $\alpha$ will have different forms as shown in Table 2.

**Table2 Stellar Spreading Angle in Various Imaging Circumstance**

| Case | MTF | Spreading angle | Expression |
|---|---|---|---|
| Long-exposure | $\tau_L$ | $\alpha_L$ | Fig. 2 (Curve $A$) |
| Short-exposure | $\tau_S$ | $\alpha_S$ | Fig. 2 (Curve $B, C$) |
| Diffraction limit | $T(f)$ | $\alpha_D$ | $1.27\lambda/D$(Curve $D$) |
| Atmosphere limit | $B(f)$ | $\alpha_\infty$ | $1.27\lambda/r_0$ |
| Image motion | $P(f)$ | $\alpha_m$ | $2\sigma_m$ |

where $\sigma_m$ is the rms image motion; $\alpha_m$ is the stellar spreading angle caused by image motion; $\alpha_S$ is the short-exposure stellar spreading angle; $\alpha_D$ is the spreading angle for diffraction limited telescope; $\alpha_\infty$ is the spreading angle for atmospheric limited case.

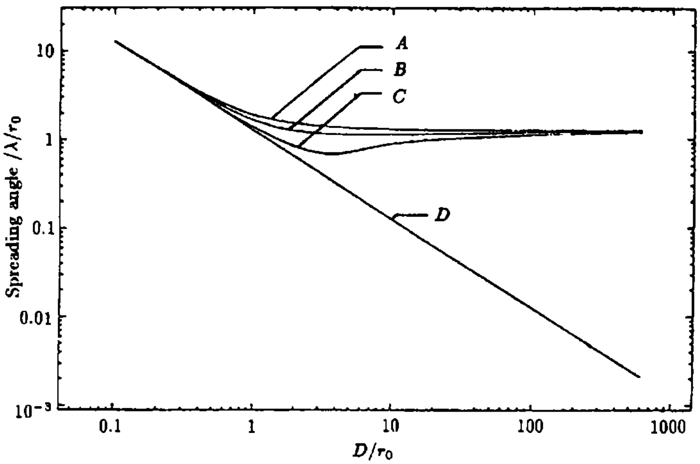


Fig.2 Spreading angle vs. $D/r_0$ (see text for the definition of $A$, $B$, $C$ and $D$)

From figure 2, when $D/r_0$ is small, the telescope itself plays a great role in image spreading while for large $D/r_0$, the spreading is caused mostly by atmosphere.

By statistic analysis of the fluctuation of arrival angle, the relationship between $\sigma_m$ and $r_0$ is given by[11,34]

$$\sigma_m^2 = 0.358(\frac{\lambda}{D})^{1/3}(\frac{\lambda}{r_0})^{5/3}, \tag{20}$$

This expression was one of the basic equations in conventional atmospheric theory for calculating the seeing parameter in site selection campaign in 1960's and 1980's[35-38].

# 4 New Turbulence Observation and Star Images

## 4.1 Atmospheric observation and finite outer scale effect

Conventional atmospheric turbulence theory for astronomy has two main assumptions. One is that the turbulence structure has a Kolmogrov spectrum, which means that the turbulence is mainly developed in an inertial range and its spatial scales lie between some large scales at which the turbulence is created and some small scales at which the turbulent motion is dissipated by the viscosity of the air. The turbulence within this two scales is assumed to be local homogeneous and isotropic. Another is that the outer scale of turbulence, $L_0$, is considered to be much larger than the aperture of the largest telescope[1,11,39]. However, both theory and observation indicate that, at low altitudes, the outer scale is of the same order of magnitude as the height above ground.

Measurements 1 or 2m above the ground show an outer scale of about 1 meter. As height increases, the outer scale increases to tens or hundreds of meters and then becomes fairly constant with height[40−43]. However, the magnitude of outer scale above the ground surface, the behavior of the power spectrum of phase at large scale sizes, and their dependence on meteorological parameters and geographical properties are all not well characterized. Typically, the size of $L_0$ is about meters to kilometers depending on the quality of a site.

Yet for astronomical observation, the new generation of giant telescopes have much greater apertures, and the size of outer scale may be of great effect, especially near the ground. Turbulence will have influence on the seeing and atmospheric modulation transfer function. The conventional assumption may not valid in this case. For optical interferometer, the maximum fringe amplitude may directly limited by the outer scale if the baseline is greater than the outer scale. Many researchers have made efforts on this[44−48], but it is uneasy to completely understand the nature of turbulence spectrum.

### 4.2 The new star image and new turbulent theory

4.2.1 Observational phenomena

Based on his considerable experience with the 100-inch telescope on Mount Wilson and the 200-inch on Palomer Mountain, British researcher Roger F. Griffin has expressed his doubts about the primary of atmospheric turbulence in degrading telescope images in 1973[49], and re-emphasized this phenomenon in 1990[16]. Griffin described: “The larger the telescope and the better its optics, the more often can starlight be concentrated in an image core whose smallness is limited by the optical tolerances of the telescope instead of the seeing”. This fact is obviously incompatible with conventional theory. Beckers and Williams[50,51,52] also have described cores in star images while using the Multiple Mirror Telescope(MMT). In fact, this phenomenon is related to the properties of outer scale of the turbulence. Conventional theory assumes that turbulence involves moving air masses ranging in size from less than a centimeter to many tens of meters. Yet recent measurements suggest that most of the turbulent energy is concentrated in structure less than a meter across. A small turbulent scale implies a restriction of the range within which Kolmogrov theory of turbulence may be applied to estimate atmospheric seeing limitations to large-aperture telescopes.

When turbulence is made up of both small and large structures, the light wavefronts entering a big telescope have large peak-to-valley variations– typically 5 microns. When the turbulence is composed of mostly small structures, the wavefronts have much smaller peak-to-valley variations– typically 1 micron. At visible wavelengths wavefront distortions produced by either kind of turbulence structures are greater than the wavelength, so the image formed in the focal plane of a ground-based telescope will be blurred. But at 2 microns in the near infrared the situation is dramatically different. Images will be badly degraded when the wavefronts have 5 microns peak-to-valley variations, but they will be only partially degraded when the variations are 1 micron and therefore smaller than the wavelength of light being observed. In such cases about half of the star's light should focus in the core—the image that would be formed by the telescope in the absence of seeing—and the rest should scatter into a diffuse halo which has the size of typical seeing disk.

4.2.2 New atmospheric turbulence model and MTF

On the basis of small turbulent outer scale, McKechine proposed a new model and developed some new predictions about atmospheric imaging that challenge many long-held ideas about imaging with large ground-based telescopes[17,18]. High resolution image could be achieved according to this theory, especially at the near infrared wavelengths. In the wavelength range 1–2 microns, 0.05 to 1 arc-second resolution is expected routinely with large (3–5m) telescope by the use of direct imaging technique even though the seeing at visible wavelength may be about 1 arc-second.

In the new atmospheric model , the atmosphere is assumed to have layered structure, and each layer is regarded as a phase screen. Two requirements are needed about the thickness of the layer.

(1) The thickness of each layer needs to be much greater than the characteristic dimension of the turbulence microstructure.

(2) The layers need to be thin enough so that they modify only the phase of a plane wave that just passed through.

If these two requirements can be satisfied together, then the atmosphere can be considered to act as a system of statistically independent random phase screens (called waveheight functions), distributed in height along the line of view.

If the waveheight fluctuations imprinted on the wavefront by the $i$th phase screen are denoted $h_i(x)$, the waveheight fluctuations imprinted by a phase screen that is equivalent to the entire atmosphere are given by the zero-mean waveheight function $H(x)$, where

$$H(x) = \sum_{i=1}^{n} h_i(x). \tag{21}$$

The equivalent phase screen can be considered to lie at any height in the atmosphere. The important statistical properties of $H(x)$ are $\sigma$, the rms variation of $H(x)$, and $\rho(\omega)$, the autocorrelation function of $H(x)$. These quantities are defined as follows

$$\sigma^2 = < H(x)^2 >, \tag{22}$$

$$\rho(\omega) = \frac{< H(x+\omega)H(x) >}{< H(x)^2 >}, \tag{23}$$

where $<>$ denotes the ensemble average.

The atmospheric modulation transfer function then can be reduced to have the following forms

$$B(\omega;\lambda) = \exp\left\{-\frac{4\pi^2\sigma^2}{\lambda^2}[1-\rho(\omega)]\right\}. \tag{24}$$

It can be shown that $\sigma$ and $\rho$ govern many of the intensity properties of star image, and they are called seeing parameters in the new model. It is also shown that $\rho(\omega)$ can be approximated by a Gaussian function

$$\rho(\omega) = \exp(-\frac{\omega^2}{\omega_0^2}), \tag{25}$$

where $\omega_0$ has the same order of size of $L_0$, the outer scale of atmospheric turbulence.

4.2.3 Intensity profile and cores in star images

The intensity profile is given by the Fourier transform of the system MTF (equation (11)),

$$\langle I(\alpha;\lambda)\rangle = 2\pi \int_0^D B(\omega;\lambda)T(\omega;\lambda)J_0(\frac{2\pi\alpha\omega}{\lambda})\omega d\omega, \tag{26}$$

where $T(\omega;\lambda)$ is the telescope MTF, $\alpha$ is the angular coordinate in image space.

If the large telescope has a central obstruction of diameter $d$, and the telescope optics causes less image degradation than does the atmosphere, the equation(26) can be written in a form

$$\begin{aligned}\langle I(\alpha;\lambda)\rangle &= (\lambda_0/\lambda)^2 \exp\left(-\frac{4\pi^2\sigma^2}{\lambda^2}\right)[P(\alpha;\lambda) \\ &+ \frac{4\omega_0^2}{(D^2-d^2)}\sum_{n=1}^{\infty}\frac{(2\pi\sigma/\lambda)^{2n}}{nn!}\exp\left(-\frac{\pi^2\omega_0^2\alpha^2}{n\lambda^2}\right)\Bigg],\end{aligned} \tag{27}$$

where $P(\alpha;\lambda)$ is the image profile inherently associated with the telescope in the absence of atmosphere, normalized to unity for no aberration. $P(0;\lambda)$ can be considered as the Strehl intensity inherently associated with the telescope.

Equation (27) shows that the intensity profile comprises two terms; One is an image core containing the fraction $\exp(-4\pi^2\sigma^2/\lambda^2)$ of the total energy whose shape is governed by the $P(\alpha;\lambda)$; Another is a halo containing the remaining part of the light energy whose width is generally of the order of the seeing disk diameter at visible wavelength.

When $\sigma/\lambda > 1$, cores are not present because only a small proportion of the total light energy appears in the core. When $\sigma/\lambda << 1$, strong cores will be present in the image plane.

The detectability of the core, $E$, can be defined as the ratio of the core brightness to the background halo brightness($a/b$ in Figure 3). Equation (27) enables $E$ to be expressed as[50]

$$E = \frac{(D^2-d^2)P(0;\lambda)}{4\omega_0^2\sum_{n=1}^{\infty}\frac{(2\pi\sigma/\lambda)^{2n}}{nn!}}. \tag{28}$$

The fraction of energy in the core is given by $\exp(-4\pi^2\sigma^2/\lambda^2)$, where the value of $\sigma$ can be approximated to

$$\sigma \simeq \frac{1}{4}\omega_0(\text{FWHM}). \tag{29}$$

Let $\omega_0 = 0.25$, then we can calculate the dependence of $E$ on the $\sigma/\lambda$. The result is given in Figure 4, where the y-coordinate is the reduced detectability $E$' (defined as $E/(D^2 - d^2)P(0;\lambda)$).

From Fig.4, we can see that at longer (infrared) wavelengths, where $\sigma/\lambda$ takes smaller values, a large fraction of the light energy is expected in the core. At infrared wavelengths, therefore, cores are expected to dominate the center of the image.

Taking $\omega_0 \sim 0.25$m means that the turbulence has small outer scale. In conventional theory, the $L_0$ is considered to be larger enough, therefore, the core will never appear.

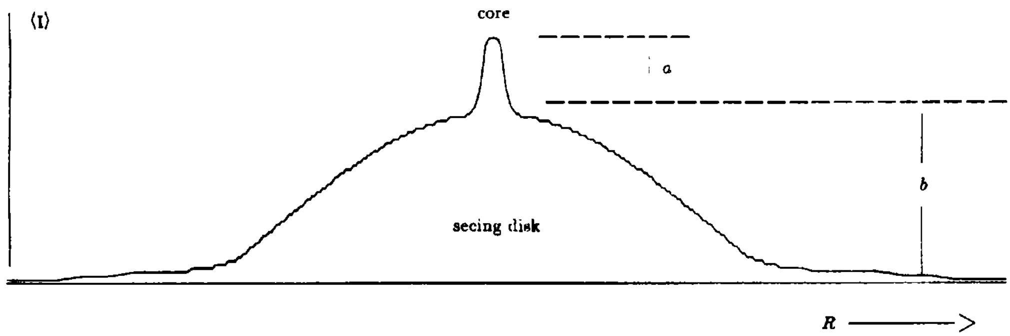


Fig.3 The definition of core detectability $E = a/b$[17]

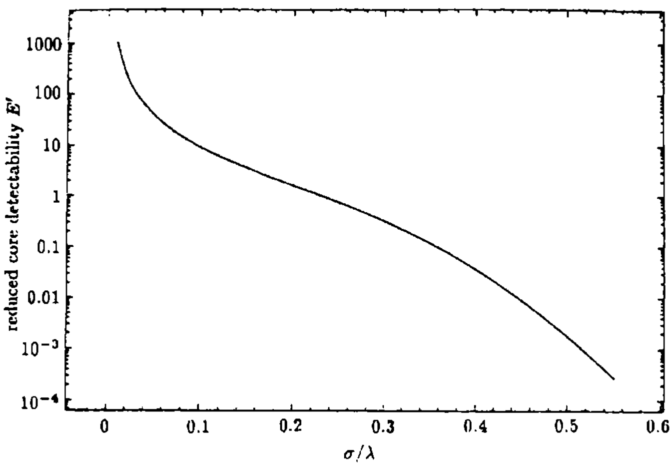


Fig.4 The dependence of reduced core detectability $E$' on $\sigma/\lambda$
(see text for definition of $E$' and reference [17] for $E$)

# 5 Conclusions

If new observational phenomenon and the theoretical predictions are confirmed, there will be great impact on the ground-based astronomy. For new generation giant telescope, it is not uneasy to achieve diffraction limited resolution as long as the telescope optics are good enough. In exceptionally good seeing condition, the presence of cores at visible wavelength might even allow resolution approaching $0''.01$ which is better than what Hubble or adaptive optics can deliver. Much more observations are needed to test the new theory, including high quality imaging with large telescope and precise measurements of the outer scale of atmospheric turbulence.

The new observed phenomenon has great application potential, especially for the telescope guiding and tracking[18]. Observations showed that the infrared cores are quite stable although the seeing-spread star images wander and boil due to the wavefront perturbation. For double stars observation, the angular distance between two image cores remains unchanged even though the real angular distance might reach several arc-minutes. This means that the infrared cores associated with the relatively few bright stars in the sky could be used to guide long-exposure images over wide neighboring areas. Meanwhile, by using cores as the reference sources, the telescope tracking performance could be greatly improved.

Astronomy is not the sole field for turbulence study. Atmospheric physicists have long devoted themselves to the research about laser propagation through turbulent media. Although Kolmogorov's classical theory is still the basis to describe atmospheric turbulence, some turbulence conditions exist for which the experimental data do not support it. At present, astronomy-related studies about turbulence are mainly concentrated on the following areas:

(1) Correcting the Kolmogorov turbulent spectrum which is not converged at origin. One of the non-Kolmogorov spectrum is the von Karman spectrum, which is the modified Kolmogorov spectrum. The new spectrum can then be used to study the characteristic quantities of atmospheric turbulence, such as coherent length and time, isoplanatic angle and modulation transfer function of the atmosphere[53,54].

(2) Measuring the outer scale of turbulence as well as its variations with height above ground. Common techniques are the interferometry and stellar scintillation measurement. Meanwhile, the real effect of outer scale on telescope imaging through turbulent atmosphere is also being explored by astronomers.

(3) Studying the amplitude variation when light wave passes through the Earth's atmosphere, so as to have a better understanding about microstructure of turbulence at high altitude.

(4) Understanding the relationship between turbulent activity and small/large scale variations of meteorological parameters. Establishing some basic turbulent models to forecast the seeing quality from daily meteorological data[12−15]. This would greatly improve the efficiency of astronomical observation.

(5) Adaptive optics is developed to improve telescope angular resolution. This also makes it possible to acquire good knowledge about how the turbulent atmosphere causes the image degradation.

**Acknowledgement** The author wishes to thank professors Su Hongjun and Hu Jingyao for providing helpful comments about this subject. Special thank is given to professor Wan Tongsan for his careful reading and corrections to the English version of the paper.

## References

[1] Tatarski V I. Wave propagation in a turbulent medium. New York: McGraw-Hill, 1961
[2] Hufnagel R E, Stanley N R. J. Opt. Soc. Am., 1964, 54: 52
[3] Fried D L. J. Opt. Soc. Am., 1966, 56: 1372
[4] Fried D L. J. Opt. Soc. Am., 1966, 56: 1380
[5] Fried D L, Mever G E, Keister Jr M P. J. Opt. Soc. Am., 1967, 57: 787
[6] Hohn D H. Appl. Opt., 1966, 5: 1427
[7] Fried D L, Slidman J B. J. Opt. Soc. Am., 1967, 57: 181
[8] Strohbehn J W. Laser beam propagation in the atmosphere, Topics in Applied Physics, Vol.25. Berlin: Springer-Verlag, 1985
[9] Dainty J C. Laser speckle and related phenomena, Topics in Applied Physics, Vol.9. Berlin: Springer-Verlag, 1984
[10] Labeyrie A. Astron. Astrophys., 1970, 6: 85
[11] Roddier F. Prog. in Optics, 1981, 19: 281
[12] Coulman C E. Annu. Rev. Astron. Astrophys., 1985, 23: 19
[13] Columan C E, Andre J C, Lacarrere P *et al.* Publ. Astron. Soc. Pac., 1986, 98: 376
[14] Murtagh F, Sarazin M. Publ. Astron. Soc. Pac., 1993, 105: 932
[15] Murtagh F, Aussen A, Sarazin M. Publ. Astron. Soc. Pac., 1995, 107: 702
[16] Griffin R F. Sky and Telescope, May 1990, 469
[17] McKechine T S. J. Opt. Soc. Am., 1991, A8: 346
[18] McKechine T S. J. Opt. Soc. Am., 1992, A9: 1937
[19] Bufton J L. Appl. Opt., 1973, 12: 1785
[20] Coulman C E, Vernin J, Coqueugniot Y *et al.* Appl. Opt., 1988, 27: 155
[21] Coulman C E, Vernin J. Appl. Opt., 1991, 30: 118
[22] Tatarski V I, Zavorotny V. J. Opt. Soc. Am., 1993, A10: 2410
[23] McKechine T S. J. Opt. Soc. Am., 1993, A10: 2145
[24] Aime C, Borgnino J, Martin F *et al.* J. Opt. Soc. Am., 1986, A3: 1001
[25] Karo D P, Schneiderman A M. J. Opt. Soc. Am., 1978, 68: 480
[26] Scaddan R J, Walker J G. Appl. Opt., 1978, 17: 3379
[27] Parry G, Walker J G, Scaddan R J. Optica Acta, 1979, 26: 563
[28] Dainty J C, Northcott M J, Qu D -N. J. of Mod. Opt., 1990, 37: 1247
[29] Nightingale N S, Buscher D F. M.N.R.A.S., 1991, 251: 155
[30] Vernin J, Weigelt G, Caccia J C *et al.* Astron. Astrophys., 1991, 243: 553
[31] Roddier F. In: Ulrich M H, Kjar K eds. Proceedings ESO conference on scientific importance of high angular resolution vs I.R. and optical wavelength, Garching, 1981, Garching: ESO, 1982: 1
[32] Dierickx P. J. of Mod. Opt., 1992, 39: 569
[33] Roddier F, Lena P. J. of Optics, 1984, 15(4): 171
[34] Fried D L. Radio Sci., 1975, 101: 71
[35] Martin H M. Publ. Astron. Soc. Pac. 1987, 99: 1360
[36] Forbes F F, Morse D A, Poczulp G A. Opt. Eng., 1988, 27: 845
[37] Sarazin M, Roddier F. Astron. Astrophys., 1990, 227: 294
[38] Vernin J, Munoz-Tunon C. Publ. Astron. Soc. Pac. 1995, 107: 265
[39] Hu P H, Stone J, Stanley T. J. Opt. Soc. Am., 1989, A6: 1595
[40] Bouricius G M B, Clifford S F. J. Opt. Soc. Am., 1970, 60: 1484
[41] Clifford S F, Bouricius G M B, Ochs G R *et al.* J. Opt. Soc. Am., 1971, 61: 1279
[42] Blackadar A K. J. Geophys. Res., 1962, 67: 3095
[43] Fried D L. Proc. IEEE, 1967, 55: 57

[44] Consortini A, Ronchi L, Moroder E. J. Opt. Soc. Am., 1973, 63: 1246
[45] Valley G M. Appl. Opt., 1979, 18: 984
[46] Colavita M M, Shao M, Staelin D H. Appl. Opt., 1987, 26: 4106
[47] Winker D M. J. Opt. Soc. Am., 1991, A8: 1568
[48] Takato N, Yamaguchi I. J. Opt. Soc. Am., 1995, A12: 958
[49] Griffin R F. Observatory, 1973, 93: 3
[50] McKechine T S. J. Opt. Soc. Am., 1976, A66: 635
[51] Becker M, Williams J T. Proc. SPIE, 1982, 332: 16
[52] Woolf J, McCarthy D W, Angel J R P. Proc. SPIE, 1982, 332: 50
[53] Boreman G D, Dainty C. J. Opt. Soc. Am., 1996, A13: 517
[54] Song Zhengfang, Fan Chengyu. Proc. SPIE, 1994, 2222: 721