in the present paper, we have kept assumptions 1 and 4 but rejected the other two and used a more reasonable model atmosphere. Through a numerical solution of the equations of the Stokes parameters, we have calculated the profiles of the magneto-sensitive lines for FeI λ 6302.499, 6173.541, 5250.216, and compared these with observations. We have also discussed the questions 1) the verification of Uno's algebraic solution, 2) temperature sensitivity of magneto-sensitive lines and 5) magnetic broadening of magneto-sensitive lines.

1. COMPUTING PROFILES OF THE STOKES PARAMETERS OF MAGNETO-SENSITIVE LINES

The set of equations of transfer of the Stokes parameters set up by Uno is

\[
\begin{align*}
\frac{d \iota}{dr} & = (1 + \eta_1)I + \eta_2 Q + \eta_3 V - (1 + \eta_4)B, \\
\frac{d \eta_2}{dr} & = \eta_2 I + (1 + \eta_1)Q - \eta_3 B, \\
\frac{d \eta_4}{dr} & = \eta_4 I + (1 + \eta_1)V - \eta_3 B.
\end{align*}
\]

In the study of magneto-optical effects, we can regard the plane of polarization as fixed and take \( \theta = 0 \). This is why only three parameters \( I, \eta_2, \eta_4 \) appear in the above set.

In simplicity, we take \( \sin \theta = 1 \), which means that we consider only the magnetic field in the central part of the solar disc. Also, the variables \( I, \eta_2, \eta_4 \) that appear in these equations are all functions of wavelength but we have omitted the subscript for brevity.

In Eq. (1), \( \eta_1, \eta_2, \eta_4, \eta_2, \eta_4 \) are all functions of the physical parameters temperature and density.

\[
B = \frac{2h^2}{4!} \exp(k \lambda/kT) - 1
\]

\[
\begin{align*}
\eta_1 & = \frac{1}{2} \eta_2 \sin^4 \gamma + \frac{1}{4} (\eta_2 + \eta_4)(1 + \cos^2 \gamma), \\
\eta_2 & = \left[ \frac{1}{2} \eta_4 - \frac{1}{4} (\eta_2 + \eta_4) \right] \sin^2 \gamma, \\
\eta_4 & = \frac{1}{2} (\eta_2 + \eta_4) \cos \gamma,
\end{align*}
\]

where \( \gamma \) is the angle between the magnetic line and the sight line and

\[
\begin{align*}
\eta_2 &= \frac{K_2}{K}, &\eta_4 &= \frac{K_4}{K}, &\eta_2 - \eta_4 &= \frac{K_2 - K_4}{K}, \\
K_2 &= K(v) = K(v + v_H) = K(v \pm v_H), &v_H &= \Delta \lambda_H / \Delta \lambda_H, \\
\Delta \lambda_H &= \frac{2RT}{\mu + v_H^2}.
\end{align*}
\]

The Doppler half-width of a spectral line is

\[
\Delta \lambda_L = \frac{1}{c} \sqrt{\frac{2RT}{\mu} + v_H^2},
\]

The Zeeman splitting is

\[
\Delta \lambda_H = 4.67 \times 10^{-7} g H.
\]
When both the Doppler effect and damping are taken into account, the selective absorption coefficient inside a line has the expression

\[ K_L = \frac{\sqrt{\pi} c^4}{m_e^3} \frac{1}{\Delta h\rho} \left\{ e^{-\frac{2x}{\rho}} - \frac{2}{\sqrt{\pi}} \Phi(x) \right\}, \]  

(9)

where

\[ a = \frac{\Delta h}{\Delta h\rho}, \quad \delta_h = \frac{1}{4} (\gamma_1 + \gamma_2 + \gamma_3), \]  

(10)

\[ \gamma_i = \sum_{j} A_{ij}, \quad \gamma_1 = \sum_{i} A_{i1}, \quad (j < i, i < k), \]  

(11)

\[ A_{ij} = \frac{\delta_i}{\rho} \left( \frac{\delta_j e^{2x}}{\Delta h} \right). \]  

(12)

In the above, \( E_L, K_L \) and \( E_P \) are the selective absorption coefficients of respectively linear, left and right circular polarization components of a Zeeman triplet, in the usual notation.

For the oscillator strengths of Fe lines, we took the values from [5]. The collisional damping constant \( \gamma_\rho \) was calculated using the method given in Ch. 11 of [4]. What \( \Phi(x) \) gives is the atomic absorption coefficient. To find the ratio \( a \), we must change it to the mass absorption coefficient \( K_L = \frac{K_S}{\rho} \) by noting the mass of the absorbing atom. Further, we must multiply \( K_L \) by \( \frac{N_{Fe}}{N(Fe)} \) (the ratio of number of of neutral Fe atoms in the line energy state \( i \) to the total number of Fe atoms) and \( \frac{B(Fe)}{B_0} \) (ratio of number of Fe atoms in the same volume of the photosphere). The first factor is given by Boltzmann's Law and Saha's Equation

\[ \frac{N_{Fe} \mu(Fe)}{N(Fe)} = \frac{\mu(Fe)}{U(T)} e^{\frac{-E_{Fe}}{kT}}, \]  

(13)

while the second factor, by the iron content in the photosphere. As the present determinations of the iron content are not accurate, different determinations may differ from one another by one order of magnitude. We used successively the values from [2] and [6] and got \( 3.6 \times 10^{-5} \) and \( 6.2 \times 10^{-6} \) and found that the latter value gave results which agreed rather better with the observations. After these considerations, we can calculate the selective absorption coefficient for the various magneto-sensitive lines. For example...

\[ K_L = \frac{5.15 \times 10^6}{\sqrt{1 + 7.43 \times 10^{-11}}} e^{-\frac{2.88 \times 10^4 + 2.91 \times 10^{-11} V_\rho}{1 + 7.43 \times 10^{-11}}} e^{\frac{-A_{28}}{\rho}} \]  

(14)

\[ \Phi(x) = 1 - 2 e^{-x/\rho} \int_{-x/\rho}^{x/\rho} e^{x/\rho} dx. \]  

(15)

See the table in [4] gives this function only from \( v = 0 \) to \( v = 12 \), which is not sufficient for the purposes. We therefore have calculated the function up to \( v = 50 \) (see Table I). For the helium absorption coefficient \( K \), we took the value from [5] and made the necessary corrections.

For the umbral umbra, we used the atmosphere model given in [7], and for the photosphere atmosphere, we used the model synthesised in [5]. Using Adams' method, we integrated numerically from 10 to \( 10^7 \) in five thousand steps on a Chinese-made computer YX-2 to calculate the emitted profiles of the Stokes parameters \( I, Q, V \) for the line \( Fe I 4206.95 \) under various conditions with \( \tau = 0, n/6, n/4, n/3, n/2, \) and \( H = 0, 1000, 2000, 3000 \text{ and } 4000 \). Besides, for the two magneto-sensitive lines \( Fe I 6173.541 \) and \( 5250.215 \), we calculated their photospheric and spot profiles at \( B = 0 \); for any point on these profiles, we can calculate the variations of \( I, Q, V \) with \( \tau \). As an example, Fig. 1 shows the relative profile for \( I, Q, V \) (relative to the continuum intensity \( I_0 \) = \( 4.16 \times 10^{13} \) cgs) for the case of \( n/6, H = 2000 \text{ Gs} \), and the low Fe content. Since the profiles are quite normal, we have drawn only the half \( \Delta \geq 0 \). The line intensity \( I_\rho \) is \( I/\rho \) clearly shows the Zeeman splitting, while both \( R_{1/2} \) and \( R_{3/2} \) representing respectively linear and circular polarizations, show a maximum at \( \Delta = 3.12 \AA \). Fig. 2 shows the variations of the three parameters \( I, Q, V \) in the solar atmosphere. As boundary conditions, we take \( H = B \) at \( \tau = 1.0 \), and regard the incident radiation at that depth to be unaltered by the magnetic field, that is, to have zero polarisation, or \( Q = V = 0 \). After the radiation has entered the umbra, the intensity begins to decrease and approaches a...
### Table 1 (contd.)

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**Fig.1** Profiles of \( I, Q, V \) of Fe II 6302.499 \((\lambda=0.4, \theta=5000\, \text{K})\). \( I, Q, V \) at \( \Delta \lambda = 0.12 \, \text{A} \) on the profiles of Fig.1.

**Fig.2** Variations with optical depth \( \tau \) of Fe II 6302.499 \((\lambda=0.4, \theta=5000\, \text{K})\) \( I, Q, V \) at \( \Delta \lambda = 0.12 \, \text{A} \) on the profiles of Fig.1.

**Note:** By this, the correct practice of the calculated results, we must compare them with the observational data for a is Fe II 6302.499 is considered, we believe our calculated data to be basically correct, as may be seen from the following considerations:

1. **Intensity of the Continuum:** From calculations at the far wing of the line profile, we can find the spot corona continuum intensity in the 6302.4 region to be...
4.14 \times 10^{13} \text{ erg/cm}^3\text{cm.s.sterad}. This value is basically correct, for according to [10] in the same wavelength region, the photosphere at the center of the solar disk has a constant intensity of about 3 \times 10^{13} \text{ erg/cm}^3\text{cm.s.sterad} while according to [8], the ratio of the intensities in a spot umbra and in the photosphere is 0.10 - 0.15.

2. Line Profile of FeI 6302.499. We took the umbra model of [7] and calculated for a set of \( \xi \) and \( \gamma \) values the theoretical profile of FeI 6302.499, which can be compared with observed profiles. We used the solar spectrograph of the Purple Mountain Observatory and obtained spectrograms of the umbrae of the giant sunspot of 1976 March 50, and then the profile of the same line. Using a Fourier Spectrograph, Kitt Peak Observatory on March 51, recorded the same line in the same spot. According to the observations made at the Peking observatory, this spot umbra had a magnetic field of 2000 G. Since the spot was located at the center of the solar disk, we can take \( \xi = 0, \gamma = 0 \). Using these data, we took 3 different values of iron content and separately calculated the theoretical profiles. Their comparison with the observations by us and by Kitt Peak is illustrated in Fig. 5. Since the red wing of this line is affected by two superposed lines [details in [8]], we should particularly examine its violet wing. The figure shows that, the theoretical profile based on the low iron content \( 6.2 \times 10^{-6} \) agrees fairly well with the observations, though there is a certain amount of discrepancy at the wing. We shall take up this point again at the end of this section.

3. Line Profile of the Undisturbed Photosphere. The undisturbed photosphere can be regarded as approximately free of magnetic field, that is, \( \xi = 0 \). Then, \( \Delta \psi = 0 \), \( \eta_1 = \eta = \eta_0 = \eta_2 = \eta = \eta_3 \), \( \eta_0 = \eta = 0 \), and Eqs (1) become

\[
\begin{align*}
\cos \theta \frac{d\lambda}{dr} &= (1 + \eta)(1 - B), \\
\frac{d\psi}{dr} &= (1 + \eta)D, \\
\frac{d\psi}{dx} &= (1 + \eta)\psi.
\end{align*}
\]

The two equations, being mutually independent, can be solved separately. We are only concerned with the first. Using the photospheric-chromospheric model of [8] and taking two cases of the iron content, \( 6.2 \times 10^{-6} \) and \( 5.6 \times 10^{-5} \), a numerical integration of this equation gives the line profile of FeI 6302.5 of the undisturbed photosphere. For the observed data, we took the data from Jungfraujoch Observatory [10]. Fig. 4 shows the comparison between theory and observation; it shows that the lower iron content gives a better fit.
and iron, accurate numerical values have not been forthcoming. The situation and the reasons are reviewed in detail in [11]. As far as iron is concerned, the various determinations in recent years still differ greatly from one another. Of the 27 determinations of the iron content listed by Morel in 1976 [12], the largest differs from the smallest by more than one power of 10. Specifically, [5] gives $0.05/\eta_{Fe} = 5.6 \times 10^{-4}$; [13] gives $7.5 \times 10^{-4}$; [4] gives $6.23 \times 10^{-4}$; [14] gives $8.4 \times 10^{-4}$; [16] gives $8.3 \times 10^{-4}$. We find it difficult to decide what value is most reliable, while Figs. 3 and 4 show clearly that the iron content affects the calculated results greatly.

2. Errors in the Damping Constant. The damping constant includes 3 terms, radiation damping ($\gamma_r$ and $\gamma_k$) and collision damping ($\gamma_c$). All three terms contain large errors, especially $\gamma_c$. In calculating the radiation damping according to (11) and (12), we should consider separately the upper and lower transition levels of all the relevant lines, but at present, not all the $f$-values of the lines are available. We adopted the values given in [3], which are the most comprehensive of all available data, but even so, there are some two thousand lines represented. Therefore, we may have left out some lines that should have been included and this means that our calculated values of $\gamma_r$ and $\gamma_k$ can only be lower bounds. As regards collision damping, no accurate theory is available at present, especially the collisions between hydrogen and other atoms; according to the estimates in [15] and [16], the calculated values of $\gamma_c$ from pure van der Waals effect may be only 1/20 of the true values! The error in the damping constant will have a serious effect on the wing portion of the theoretical profile.

These circumstances show that our present calculations cannot be very accurate.

In reducing the spot spectrogram of 1976 March 30, we looked into the effects of the solar corona and the atmospheric seeing on the line profile. Our actual measurements, however, that both terms are small and can be neglected within the measuring error of photographic photometry.

3. EXAMINATION OF UNNO'S ALGEBRAIC SOLUTION

In [1], Unno gave an algebraic solution of the equations of transfer (1) of the same parameters:

$$
\begin{align*}
\tau(\theta) &= \frac{I(\theta, \theta)}{I(\theta, \theta)} = \frac{1}{1 + \beta \cos \theta \left( 1 + \eta \right)^{-1} - \eta}, \\
\tau(\theta) &= \frac{I(\theta, \theta)}{I(\theta, \theta)} = \frac{1}{1 + \beta \cos \theta \left( 1 + \eta \right)^{-1}}, \\
\tau(\theta) &= \frac{I(\theta, \theta)}{I(\theta, \theta)} = \frac{1}{1 + \beta \cos \theta \left( 1 + \eta \right)^{-1} - \eta}, \\
\end{align*}
$$

To understand Unno's algebraic solution, we used it to calculate the profile $\tau(\theta)$, i.e. 163502.5 in the umbra, taking $\theta = 0$, as before. According to the definition $\tau(\theta)$, we have

$$
\beta = \frac{1}{B_0} \frac{dB}{ds} = \frac{1}{B_0} \frac{dB}{ds} \frac{dT}{ds} \frac{ds}{dt}.
$$

Using the approximate model

$$
\tau = T^2 (1 + \frac{3}{2} g),
$$

we calculate the line profiles $\tau(\theta)$. We made such calculations for three cases: 1) $\gamma = 4 / 2$, $\eta = 100$, 2) $\gamma = 0$, $\eta = 100$, and 3) $\gamma = 0$, $\eta = 100$. The results for the last two cases are shown in Fig. 5. It shows that the profiles based on Unno's algebraic solution and numerical solution are considerably different from one another. The most striking differences are: 1) in cases 1) and 2), Fe I 163502.499 should show clear triple line splitting, especially 2) where it is a purely transverse Zeeman effect. Our numerical
line centre: our solution gave 0.42 while Umm's, only 0.01. Such a deep line cannot arise in the solar spectrum.

This shows that Umm's algebraic solution is comparatively coarse and results derived therefrom (e.g., interpretation of magnetograph data) should be seriously re-examined. There is a serious problem in the study of the solar magnetic field.

Why is the difference between the two solutions so large? We believe the main reason is that Umm's assumptions of constant $\Delta \pi$ and $\pi$ are far from reality. To clarify this point, we calculated, for the umbra model of [7], the values of the Planck function and of $\phi_0$ at different optical depths; the results are given in Table 2. This Table shows that $\phi_0$ in the umbra varies greatly from 0 to 404. The situation is similar for $\pi$. Therefore, by taking them to be constant, serious distortion will result. Also, while the Milne-Eddington model can generally be used in the central region of the strong lines, where the radiation mainly comes from the upper or shallower layers of the atmosphere and $\pi$ and $\phi_0$ can, as a consequence, be regarded as constants independent of depth, the magneto-sensitive lines are all rather weak lines, and their emission, whether in the core or the wing, is synthesised from the various layers of the atmosphere, and so the Milne-Eddington model is not suitable for the magneto-sensitive lines. This may also be the root of trouble in Umm's algebraic solution.

### Table 2: Variation of $\phi_0$ with Optical Depth $\tau$

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<td>6.3</td>
<td>8.1</td>
<td>11</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>$\Delta \pi$</td>
<td>16.4</td>
<td>21.9</td>
<td>30.4</td>
<td>40.5</td>
<td>54.8</td>
<td>73.0</td>
<td>97.2</td>
<td>132</td>
</tr>
<tr>
<td>$\Delta \phi_0$</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
<td>3.4</td>
<td>3.6</td>
<td>3.8</td>
<td>4.0</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>205</td>
<td>264</td>
<td>327</td>
<td>378</td>
<td>389</td>
<td>404</td>
<td>314</td>
<td>0.00</td>
</tr>
</tbody>
</table>

In our numerical solution, we abandoned the unrealistic assumptions of constant $\Delta \phi_0$ and $\pi$, and used a more realistic model atmosphere and so naturally obtained better results. However, up to now, we still kept Umm's other assumptions, such as that of a constant $\Delta \pi$, independent of depth. We hope to make improvements on these questions in a future work.

The calculated profiles of the parameter $\gamma$ of 36502.5 for $\gamma = 0$ and $\gamma = 1000$, 2000, 3000, 4000 are shown in Fig. 6, while Fig. 7 shows the variation with the field strength of the location of the profile maximum, $(-\gamma^b)_{\text{max}}$, and its distance from the centre of the line, $(\Delta \gamma)_{\text{max}}$. With such data, we can now determine the field strength $H$ from the $\gamma$-profile of the line. The determination will be much more accurate than using the width of the Zeeman splitting $(\Delta \gamma)_{\text{max}}$.

**4. Temperature Sensitivity of Magneto-Sensitive Lines**

The question of temperature sensitivity of magneto-sensitive lines first arose in the late 1920s in connection with FeI 5250.216. During the previous ten years, solar magnetograph spectrograms were mainly of this line. It was eventually found that the line was not only sensitive to the magnetic field ($g = 3$) but also to temperature. Regions with different fields may have different temperatures, and both factors will distort the line profile. Hence, if we disregard the atmospheric effects of temperature sensitivity is overlooked and the magnetic field is wrongly taken to be the sole cause for the shape in the line profile, the results will be very unreliable. It was pointed out in [17] that the field measured in 5250 was smaller than the true value, the difference is a factor of 2 in the wing and 5 at the centre! The question is serious.

Of course, temperature sensitivity is not confined to this line. In [18], Wittmann used the ratio of the equivalent widths of a given line in the umbra and in the photosphere, $W_1 / W_2$ as a measure of the temperature sensitivity, and calculated these ratios for a series of lines. We find that Wittmann's procedure is not entirely satisfactory, because both field and temperature variations can affect the profile, hence the equivalent width of a line. In order to bring out the temperature sensitivity, one should subtract the effect of the magnetic field. Therefore, in calculating the equivalent width, we must purposely take $H = 0$, that is, we must evaluate $W_0 = W_{10}$. The results of our calculation in this manner on three magneto-sensitive lines are shown in Figs. 8 and 9, and Table 3. We see from these that the temperature sensitivity of FeI 36502.499 is low, and as such, it is suited for magnetic field
measurement. The temperature sensitivity of Fe I 55250.216 is indeed high, only \( N \) value of 3.4 appears to be somewhat too high. The discrepancy may be due to certain difficulties in the profile calculation of 55250. As Dunn [19] pointed out, the lower part of this line is very low (the excitation potential is only 0.121 eV), so its core is formed in the uppermost layer of the chromosphere, which may be above the top layer of the model atmosphere. Our calculation has confirmed this point.

Recently, there has appeared a new type of magnetograph, the optical frequency magnetograph. It employs a narrow-band filter, and forms a monochromatic image inside a magnetic sensitive line. The present state of art limits the transmission band to widths not less than 0.18 A. Hence, lines as wide as possible have to be used and so far this meant only the line Fe I 5524.171 with a half-width of 0.3 A. Unfortunately, its Lande factor is rather small \( \gamma = 1.5 \). Moreover, its temperature sensitivity may be quite high. In Rowland's Table 3, this line is marked with 's' in the column Sunspot, meaning that the line strength shows in the spot spectrum, as in the case of 55250. Therefore, in order to assess the sensitivity of the data observed with the optical frequency magnetograph, the temperature sensitivity of 5524 should be calculated, and this is the next piece of work we propose to do.

5. MAGNETIC BROADENING OF MAGNETO-SENSITIVE LINES

The existence of a magnetic field affects the formation of magneto-sensitive lines; it not only changes their profiles but may also increase their equivalent widths [21-26]. To study the broadening more completely, we have calculated the line profile of Fe I 55302, for 5 values of \( B(0, 1000, 2000, 3000, 4000 \) G), and 3 angles \( \gamma (0^\circ, 30^\circ, 45^\circ, 60^\circ, 90^\circ) \), and measured their widths. Our results are summarized in Fig. 10, where the broadening is represented by the difference in the equivalent width, \( \Delta W ' \), between the field \( H \) and the zero-field. The figure shows:

![Fig. 8 Temperature sensitivity of Fe I 55302.499](image)

![Fig. 9 Temperature sensitivity of Fe I 55250.216](image)

![Table 3. Temperature Sensitivity of Magneto-sensitive Lines \( H=0 \)](image)

![Fig. 10 Field enhancement of Fe I 55302.499](image)

1. Magnetic broadening of magneto-sensitive lines indeed exists.
2. The amount of broadening \( \Delta W ' \) depends on both \( H \) and \( \gamma \).
3. When \( \gamma = 0^\circ \), \( \Delta W ' = 0 \). This shows that longitudinal Zeeman splitting is not subject to broadening. When \( \gamma \neq 0^\circ \), \( \Delta W ' > 0 \); and the larger the \( \gamma \), the larger \( \Delta W ' \) will be.
Solar Magnetic Lines

4) \(\Delta W\) tends towards saturation after \(\gamma\) passes 60°; it does not pass through a valley at \(\gamma = 55°\), as some says.

6) The saturation is more marked, the stronger the field. We feel that, as magnetic broadening indeed exists, the effect of a magnetic field on the curve of growth and decay of sunspots and magnetic stars should be further examined.

We wish to thank most sincerely Comrades Tong Fu, Wu Liang-da, Wang Chang-bin and Chen Qu for their enthusiastic help in compiling the necessary computing programs during the course of the present work.

REFERENCES


ON FROZEN-IN AND RESISTIVE FORCE-FREE MAGNETIC FIELDS

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ABSTRACT

\(\nabla \times B = \alpha B\) with the constraint that \(\nabla \times B = \alpha B\) and \(\nabla \times B = \alpha B\) which ensures that \(\frac{\partial B}{\partial t} = 0\). It will be shown that the force-free factor \(\alpha\) is a constant for a stable magnetic field.

1. INTRODUCTION

A tenacious ionised gas carries a strong magnetic field; when the pressure gradient \(\Pi\) is zero, the magnetic pressure gradient \(\Pi = \alpha\) by more than one order of magnitude its extranormal body force will be nearly zero, and we have a force-free field, whose states are

\[\nabla \times B = \omega B,\]

\[4\frac{\partial^2 B}{\partial t^2} = \nabla \times B.\]

\[\omega = \text{the force-free factor, and is, in general, a function of position and time. It is a topic of interest in both astrophysics and controlled thermonuclear reactions.}\]

It was proved by Lundquist [1] that for a static fluid whose magnetic field decays without resistance must be a constant. Chandrasekhar and Woltjer [2] proved that a force-free field \(\omega\) constant \(\alpha\) is a field with a given magnetic energy that has the smallest Ohmic dissipation. Woltjer [3], by taking the variation of the magnetic energy of a system under a force constraint, found that for a frozen-in, a constant \(\alpha\) represents a state of minimum energy and that if the fluid is static, then \(\alpha\) is a constant. The result [4] proved that for a resistive force-free field, if it is static, then \(\alpha\) is a constant. No matter what its initial state is, a mass of tenaceous conducting gas constrained by a strong magnetic field will evolve towards a state of static equilibrium when its potential energy (i.e., magnetic energy) will be at a minimum. In this paper, by taking the